Meeting Objectives

- Provide GM technical understanding of WaveCrest's E^{n}Power Motor and Propulsion System
- Demonstrate E^{n}Power Motor's performance capability
- Review product growth strategy and discuss opportunities for cooperation

Agenda

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- Introduction
- WaveCrest's Vision
- WaveCrest's Revolutionary E^{n}Power Motor
- E^{n}Power Motor Performance
- Demonstration and Tour
- E^{n}Power Propulsion System
- GM Requirements Workshop

WaveCrest's Vision

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Pressures to Improve Fuel Economy

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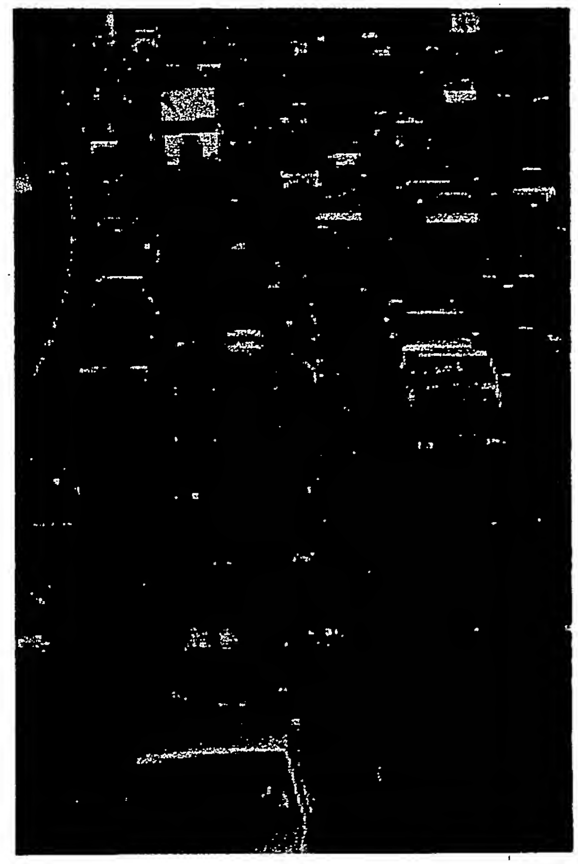
- Environmental
  - Global Warming
  - Air Pollution
- Competitive
  - Toyota Hybrid
  - Honda Hybrid
  - Fuel Cell Research
  - European Diesel Engines
- Political
  - Pressure to Tighten CAFE Legislation
  - Kyoto Accord
  - FreedomCar Initiative
  - Mideast Oil Dependency
  - California Air Resources Board



WaveCrest History

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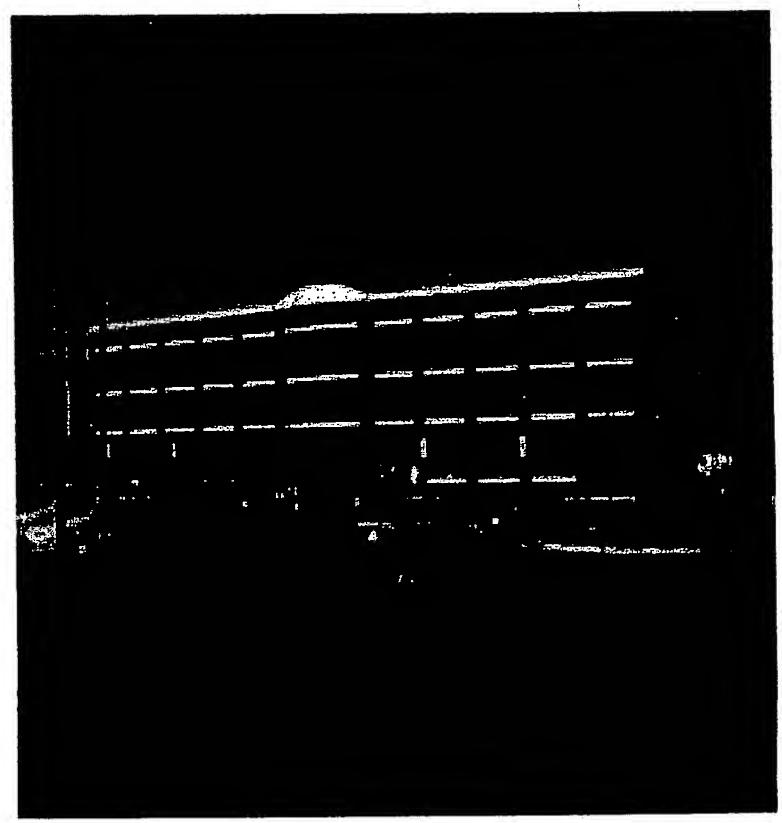
1992
- Dr. Pyntikov begins investigating alternative propulsion systems in Cyprus

1998
- Drs. Pyntikov and Maslov develop the Adaptive Motor™ system in the U.S.
- Adaptive Motors Corporation founded
- Initial technology patents filed
- Speed and torque tracking algorithms developed

2000
- WaveCrest Laboratories founded with initial funding from Allen Andersson

2001
- Light Electric Vehicle Division launched
- Initial electric bike prototypes available

2002
- First 2 patents granted; dozens more submitted and under review
- Production bikes shipped to first customers



Wavecrest's Highly Skilled Workforce...

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Bench Strength	
Masters	17
JD	1
BA	27

Engineering Competencies

- Structural
- Mechanical
- Thermal
- Metallurgy
- Electromagnetics
- Power Electronics
- Digital Signal Processing
- Analog Circuits
- Custom Chip Design
- Electronic Packaging
- EMC / RFI
- Battery Technologies
- Vehicle Dynamics

- Requirements Definition
- Architecture Development
- Design & Validation
- Simulation (FEA)
- Modeling (CAE)
- Compliance Testing
- Statistical Analysis
- Quality Assurance
- Transition to Production
- Design to Cost
- Design for Test
- Design for Manufacturing
- Six Sigma / ISO 9000

...Comes from the Biggest and Best

wavecrest
LABORATORIES

GM

Visteon

TRW

MOTOROLA

DELPHI
Driving Tomorrow's Technology

ERICSSON

EXIDE

LOCKHEED MARTIN

ABB Corporate Research and Development

Ford

NASA

DANA

British Steel Corporation

DAIMLERCHRYSLER

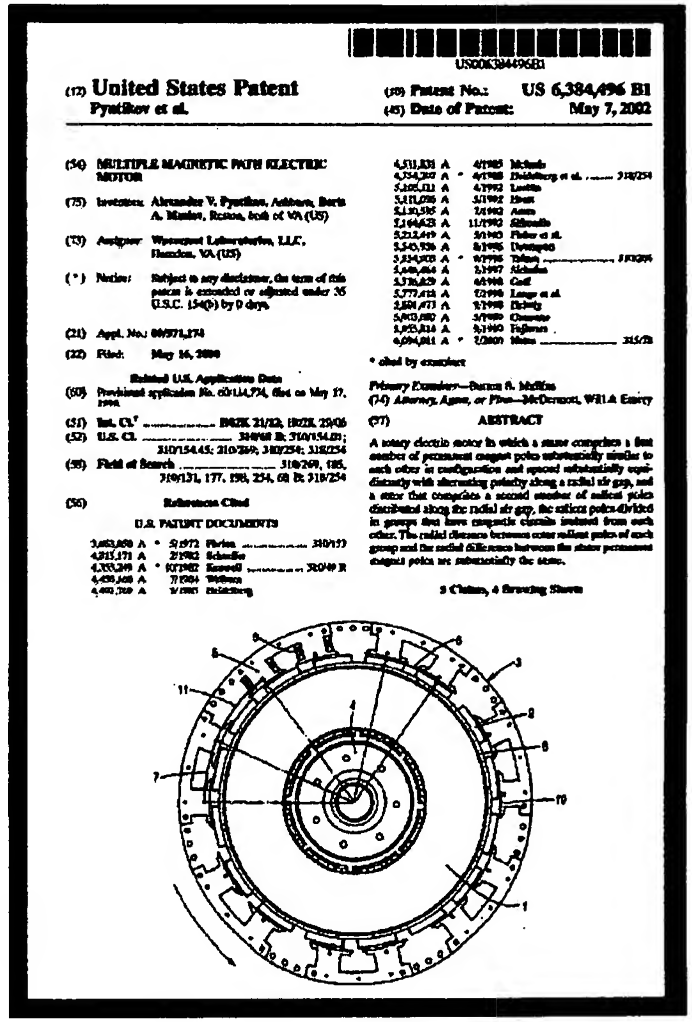
ROUSH

Intellectual Property Protection

- 2 Patents granted
- 29 Patents pending
- 53 Applications in process and/or scheduled for foreign filings
- 223 Additionally identified inventions
- 6 Trademarks pending
- Software protected by copyrights
- Trade secrets protected by Uniform Trade Secrets Act
- Comprehensive patent pending

"WaveCrest's IP rights should give its powerful, efficient, compact adaptive motors a sustainable competitive advantage for years to come."

- Ed Durney, Patent Strategies, Inc.



(12) United States Patent
Pyntikov et al.

(10) Patent No.: US 6,384,496 B1
(45) Date of Patent: May 7, 2002

(54) MULTIPLE MAGNETIC PATH ELECTRIC MOTOR

(57) ABSTRACT

WaveCrest's Vision of Electric Drive Vehicle Market

Electric Drive Vehicle Market

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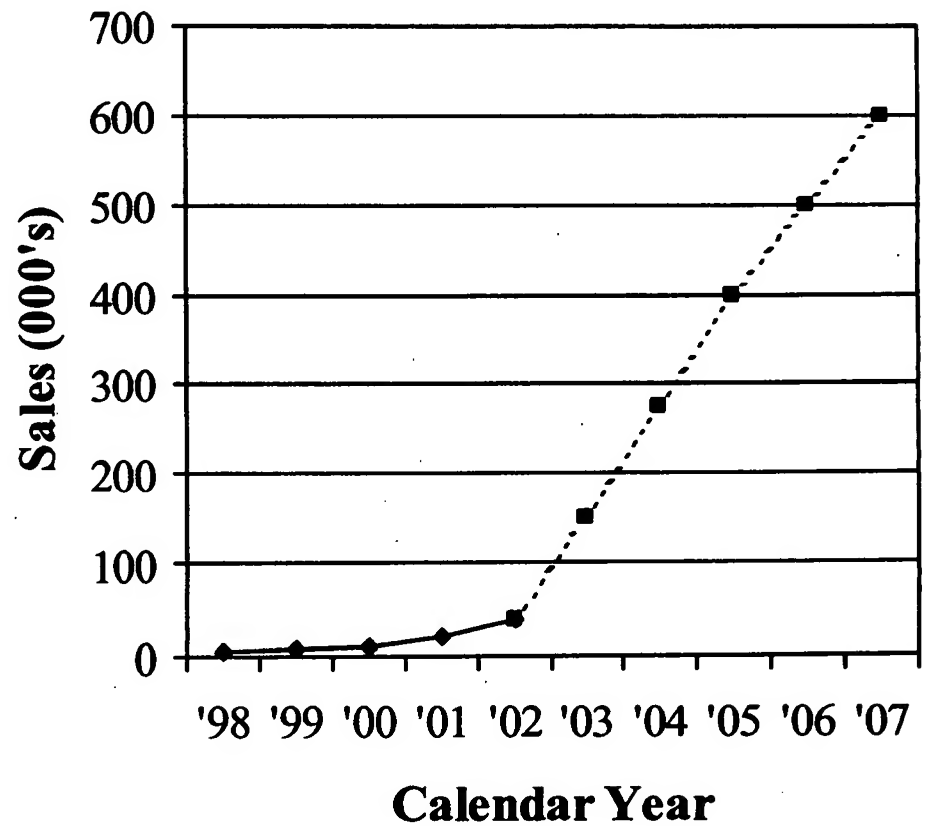
- BEV – Battery Electric Vehicles
- LSEV, NEV – Low Speed/Neighborhood Electric Vehicles
- FCEV / FCHEV – Fuel Cell (Hybrid) Electric Vehicles
- HEV – Hybrid Electric Vehicles

"Hybrid Volumes Blast Off"

Automotive News, December 23, 2002



OEM Product Plans- System Architecture

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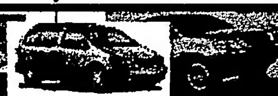
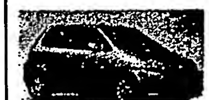
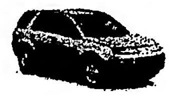
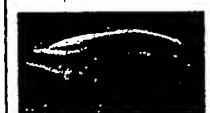
OEM	ISG	Mild HEV	Full Parallel	E-AWD	Series HEV	FCHEV
TOYOTA	 Crown (MHS) Japan		 Prius (THS) Jpn, NA, EU	 Estima; RX330		
HONDA		 Insight Japan/NA/EU  Civic Sedan Jpn, NA				
GM	 Tahoe/Silverado NA		 Vue, NA			
FORD			 Escape (NA)			
DAIMLER CHRYSLER	 Ram NA	Mitsubishi – Sebring, NA Smart MCC, EU				
NISSAN			Nissan SUV (w/Toyota THS)			
VW						

OEM Product Plans- By NA Segment

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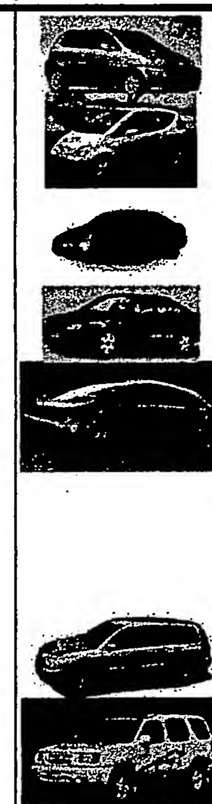
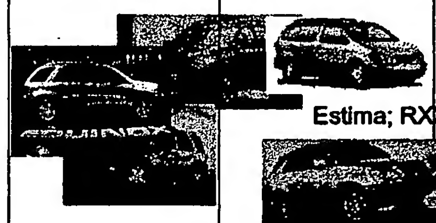
Segment	ISG	Mild HEV	Full Parallel	E-AWD	Series HEV	FCHEV
Sub Compact		 Insight Japan/NA/EU; Smart MCC, EU				
Compact		 Civic Sedan Jpn, NA	Prius (THS) Jpn, NA, EU			
Mid, Full Size	 Crown (MHS) Japan	Mitsubishi – Sebring, NA ?				
Van / Cross Over		 Vue, NA		Estima; RX330		
SUV	Tahoe/Silverado NA 		Nissan SUV (w/Toyota THS)			
Pick-Up	 Ram NA					

-13-

Consumption vs. Fuel Economy

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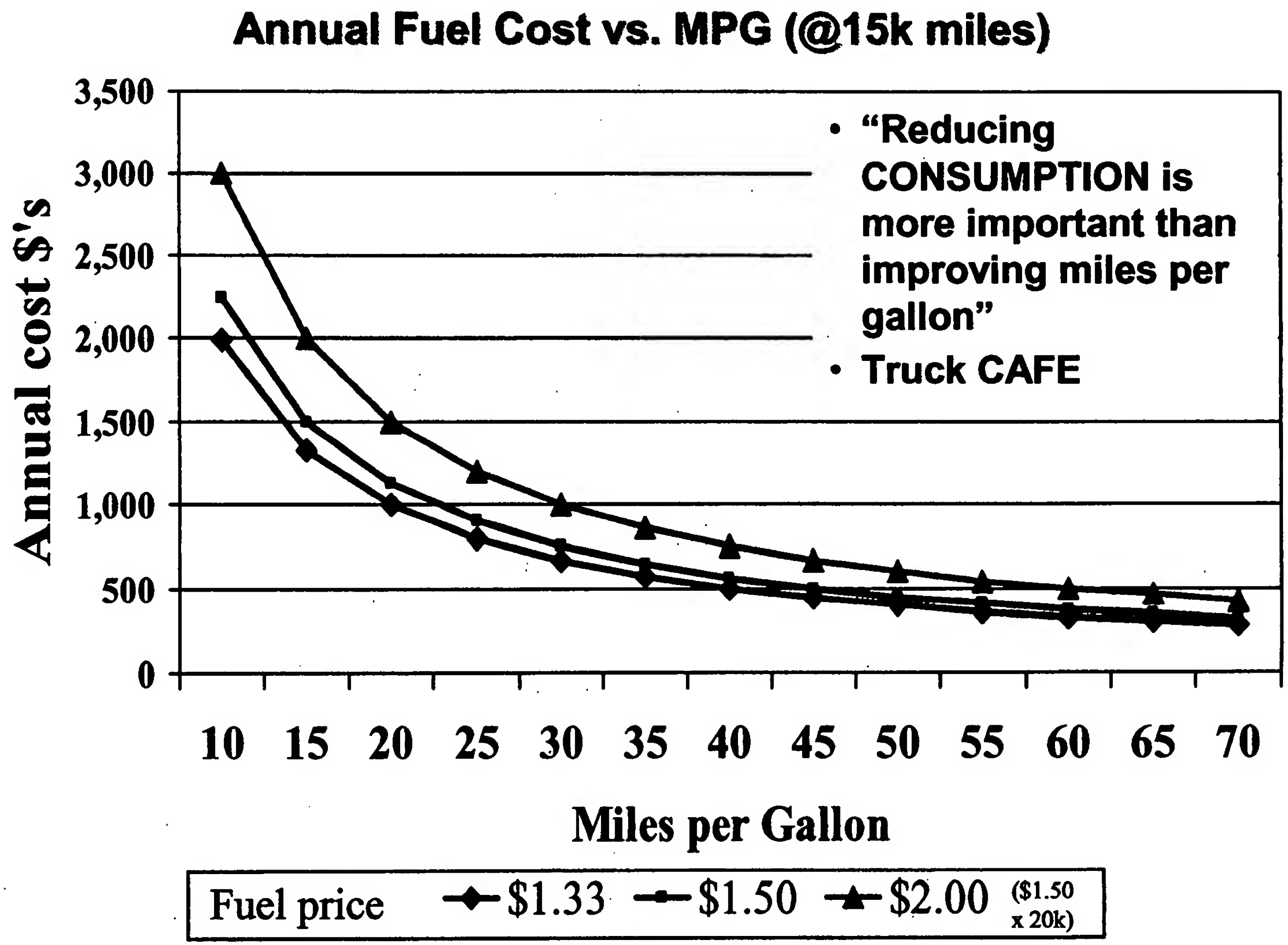

WaveCrest's Electric Drive Vision

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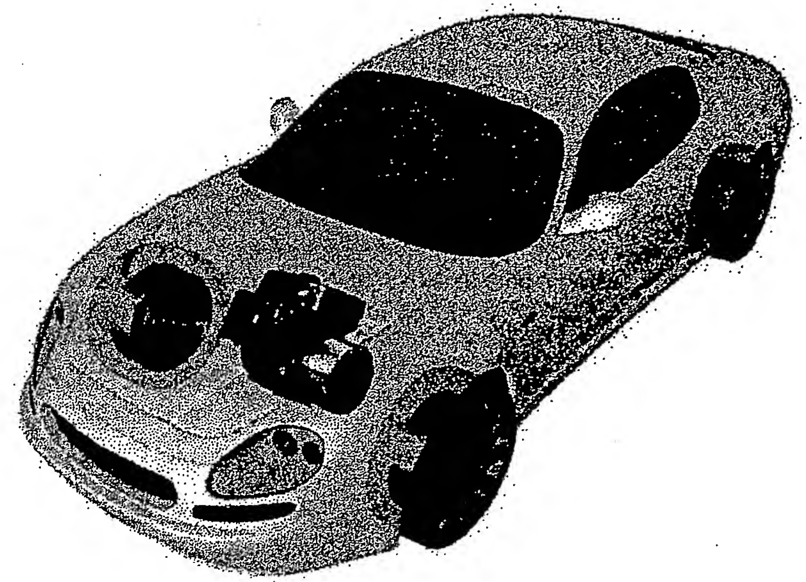
- Develop technology solution that spans multiple segments:
  - Compact/Subcompacts
  - Higher GVW SUVs/Pickups
  - Commercial vehicles and trucks
- Develop technology that is portable to fuel cell vehicles
- Provide value through a system engineering solution
  - Total energy management
  - Create value by combining functions



Systems Engineering Solution

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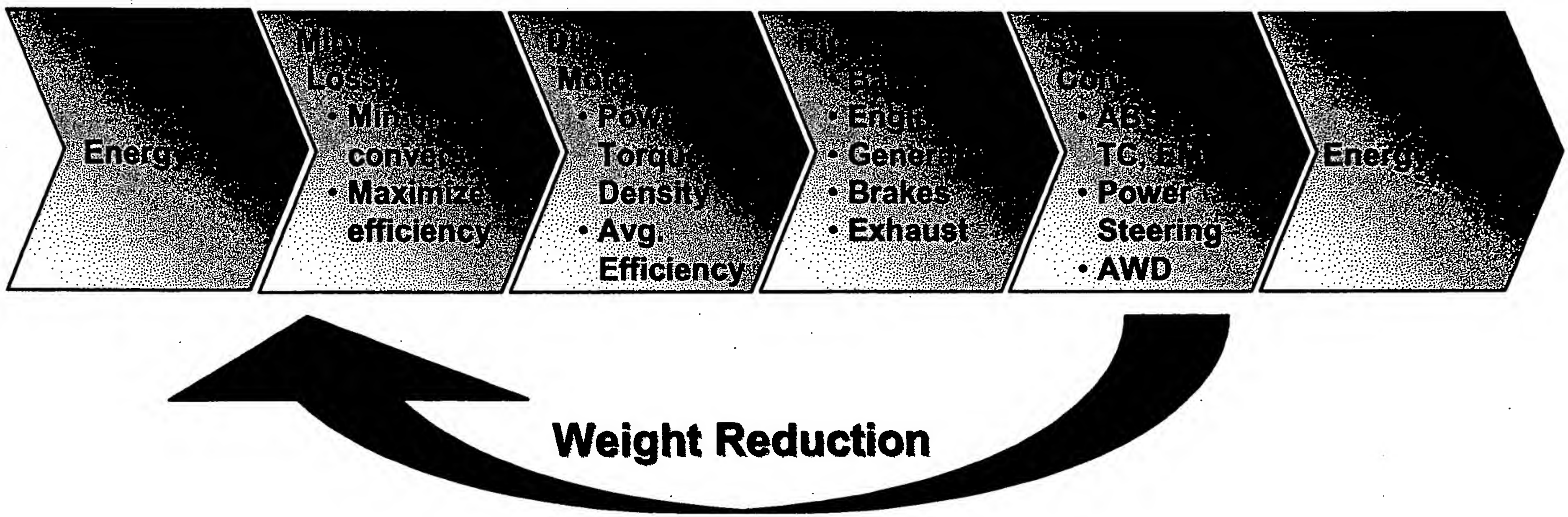
Total Energy Management Solution



WaveCrest Enablers

- Unique motor design to maximize power to volume ratio
- Leader in torque and power to weight ratio
- Highest average efficiency
- High torque and control at low/zero speed

Systems Engineering Solution

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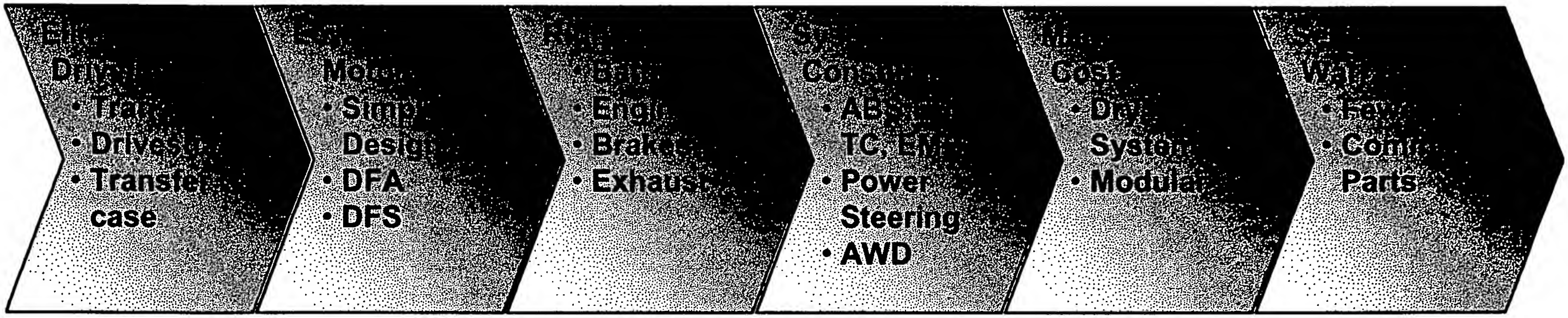
Drive Savings Across the Value Chain



WaveCrest Enablers

- Power steering, brake, transmission and gear fluids can be eliminated
- Motor designs enables mass customization

E^{n}Power Applications

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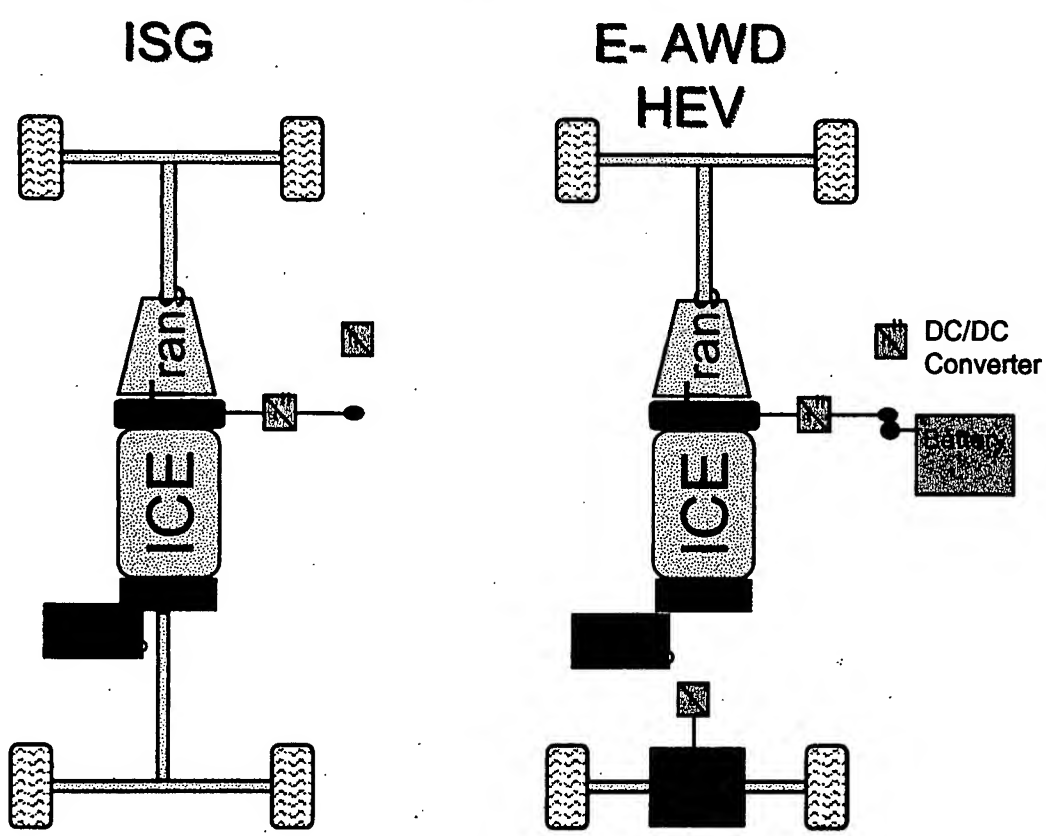
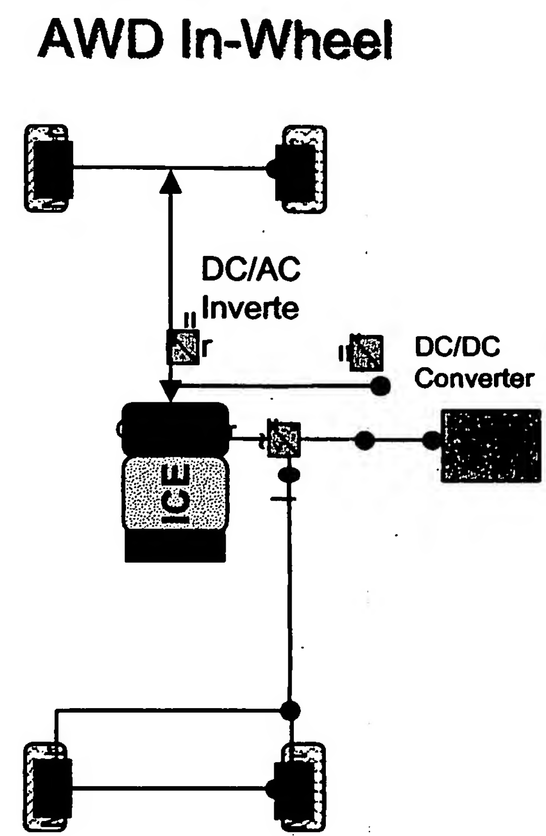
Parallel HEVs



Series HEV



WaveCrest Shares GM'S Vision

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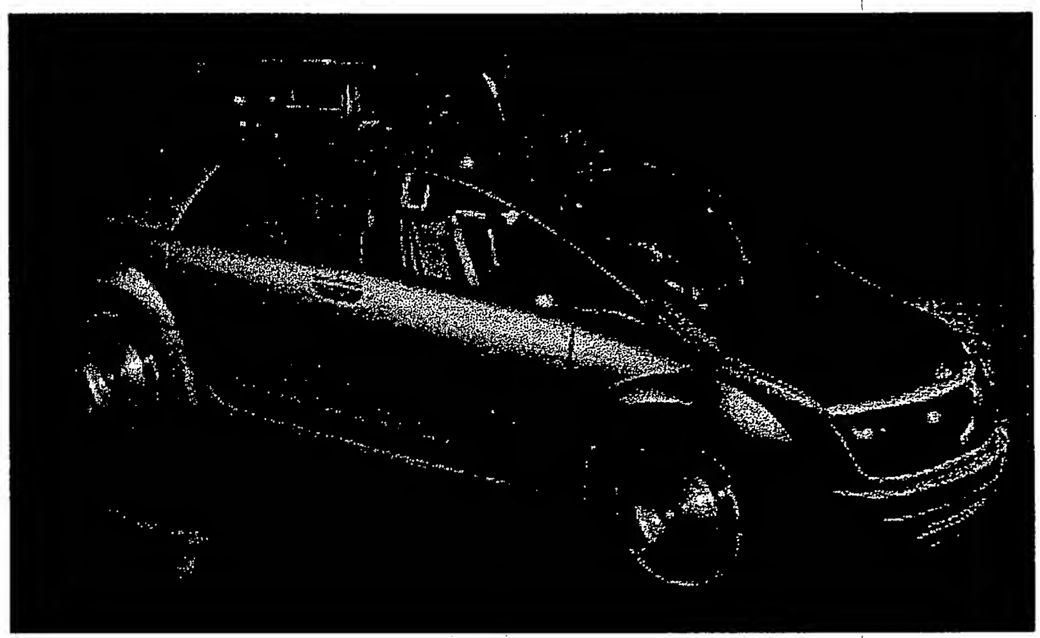

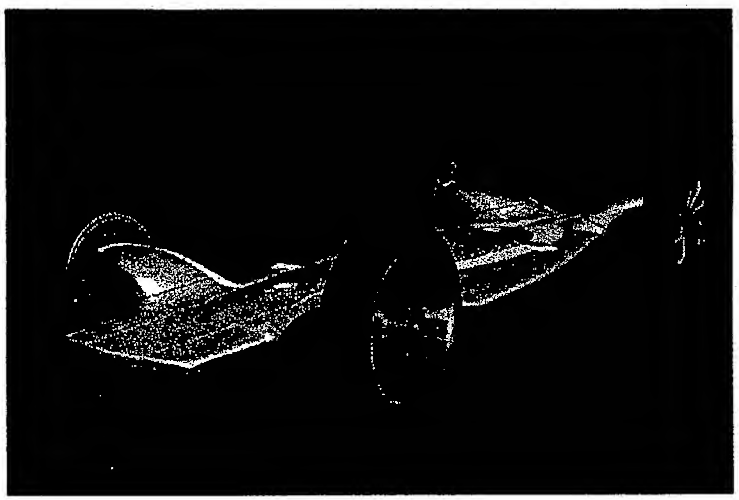

But GM understand the barriers

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“ Less mature components of the AUTOnomy chassis are the wheel motors, which Dr. Chris Borroni-Bird admits, may never happen.

‘We’d like to have it for flexibility,’ he says. But without a break-through, they’re too heavy.’ ”

– Automotive Industries, February 2002

WaveCrest's Revolutionary E^nPower Motor

E^{n}Power's Motor Design Parameters

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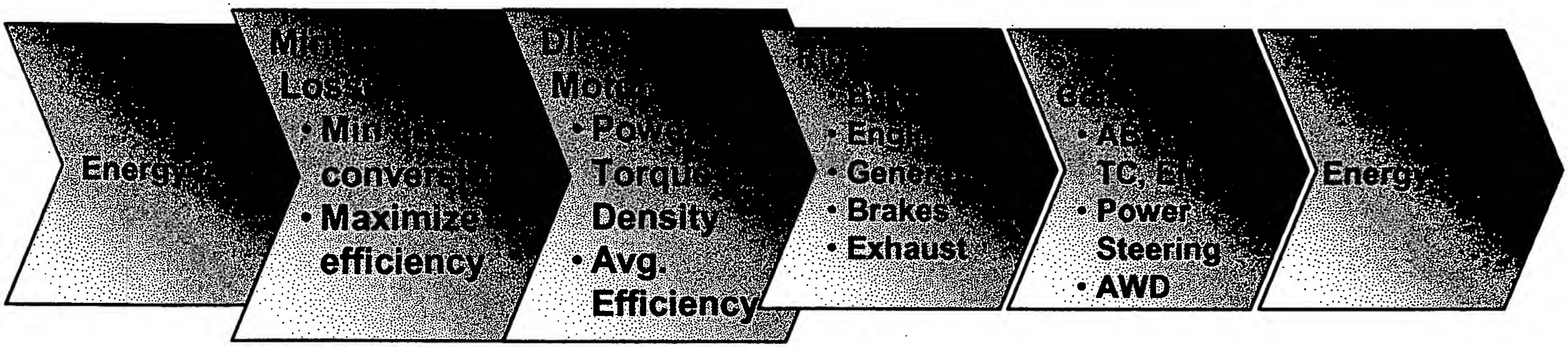
Total Energy Management Solution



- Leader in power and torque to weight ratios
- Leader in motor's average efficiency across full operating range
- In-wheel, gearless design
- Durable and reliable design
- Minimize overall system and lifecycle costs

E^{n}Power's Motor Architecture

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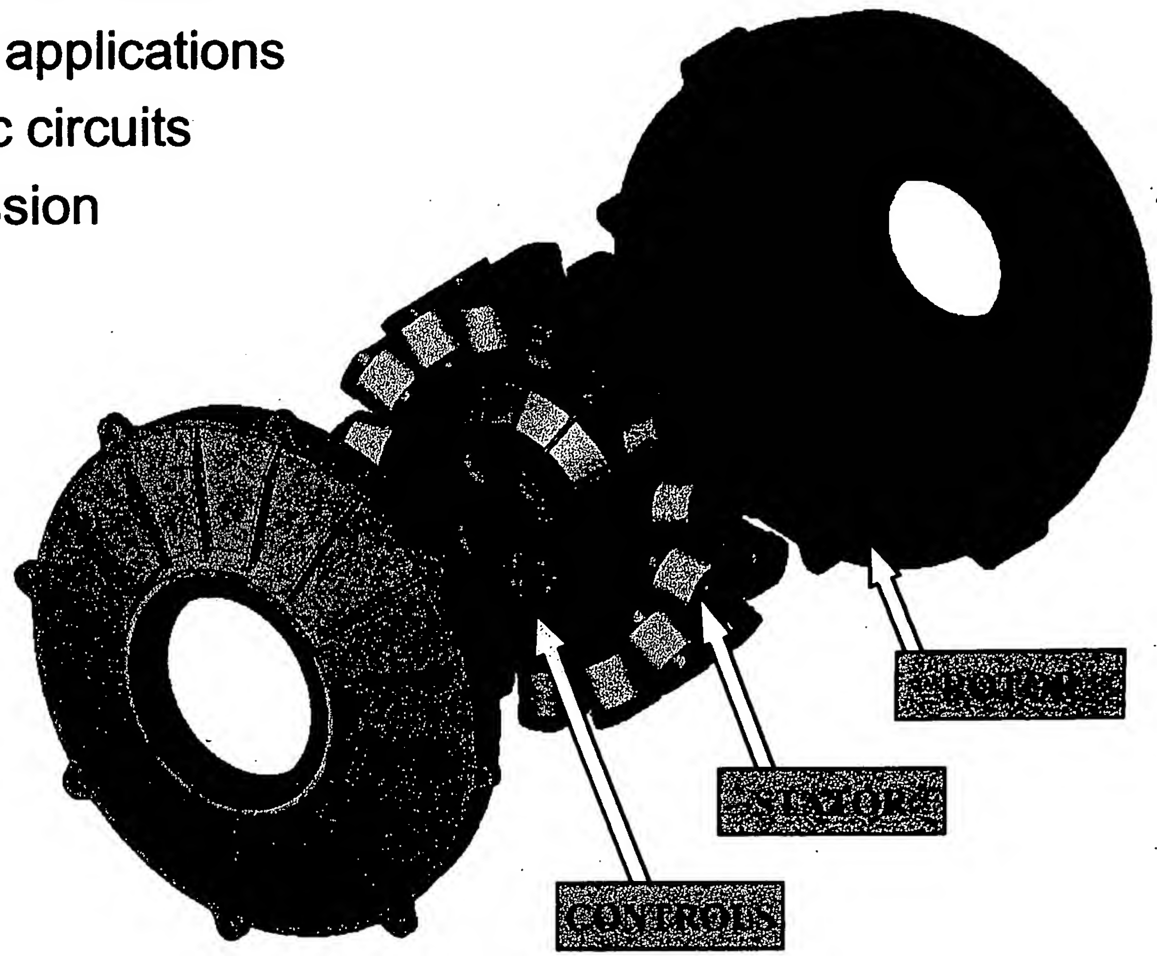
- Advanced brushless DC motor
- Inverted for in-wheel applications
- Segmented magnetic circuits
- No gears or transmission
- Low voltage

Gamma Motor



E^{n}Power's Motor Architecture

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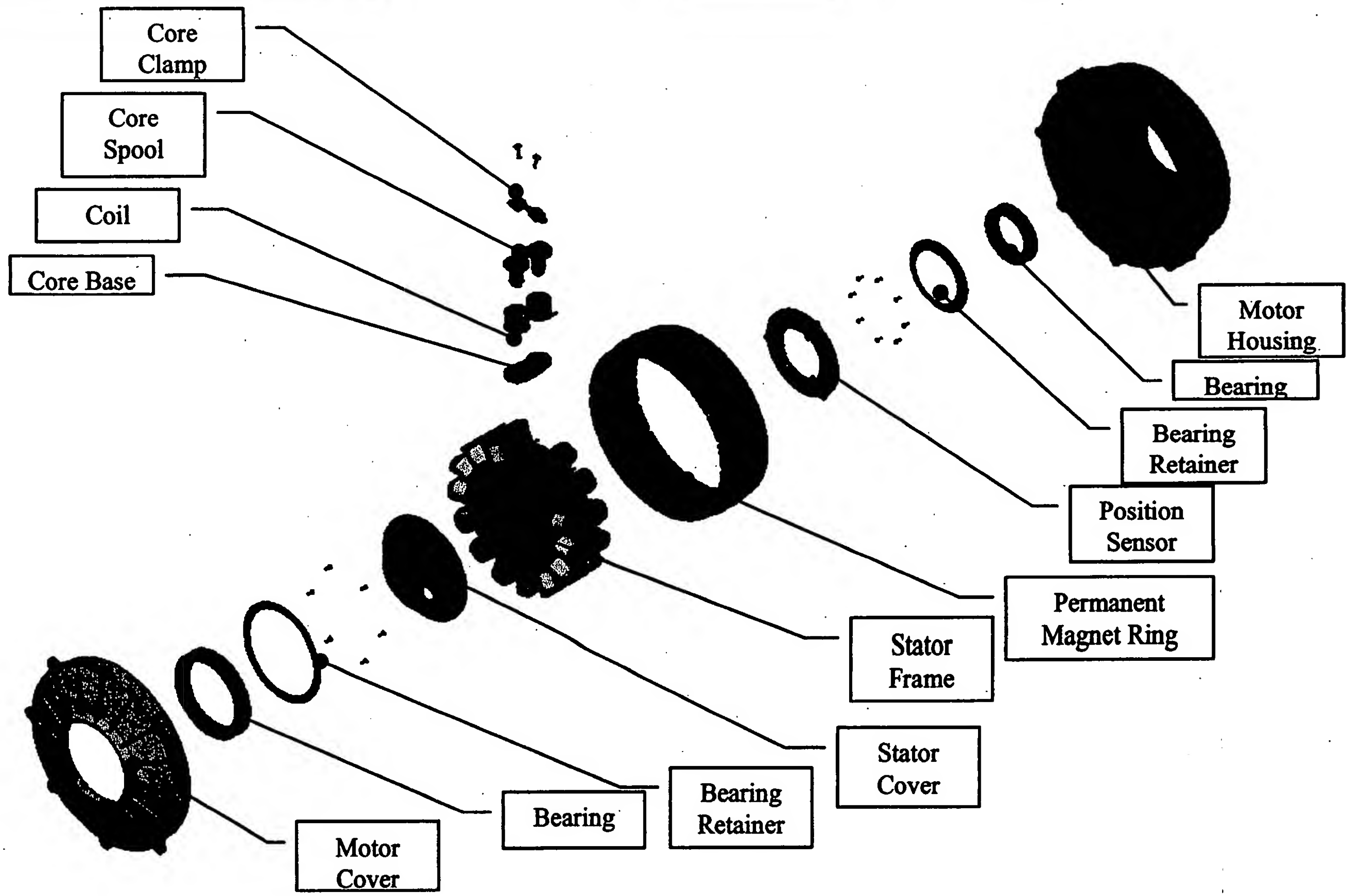

E^{n}Power's Motor Scalability

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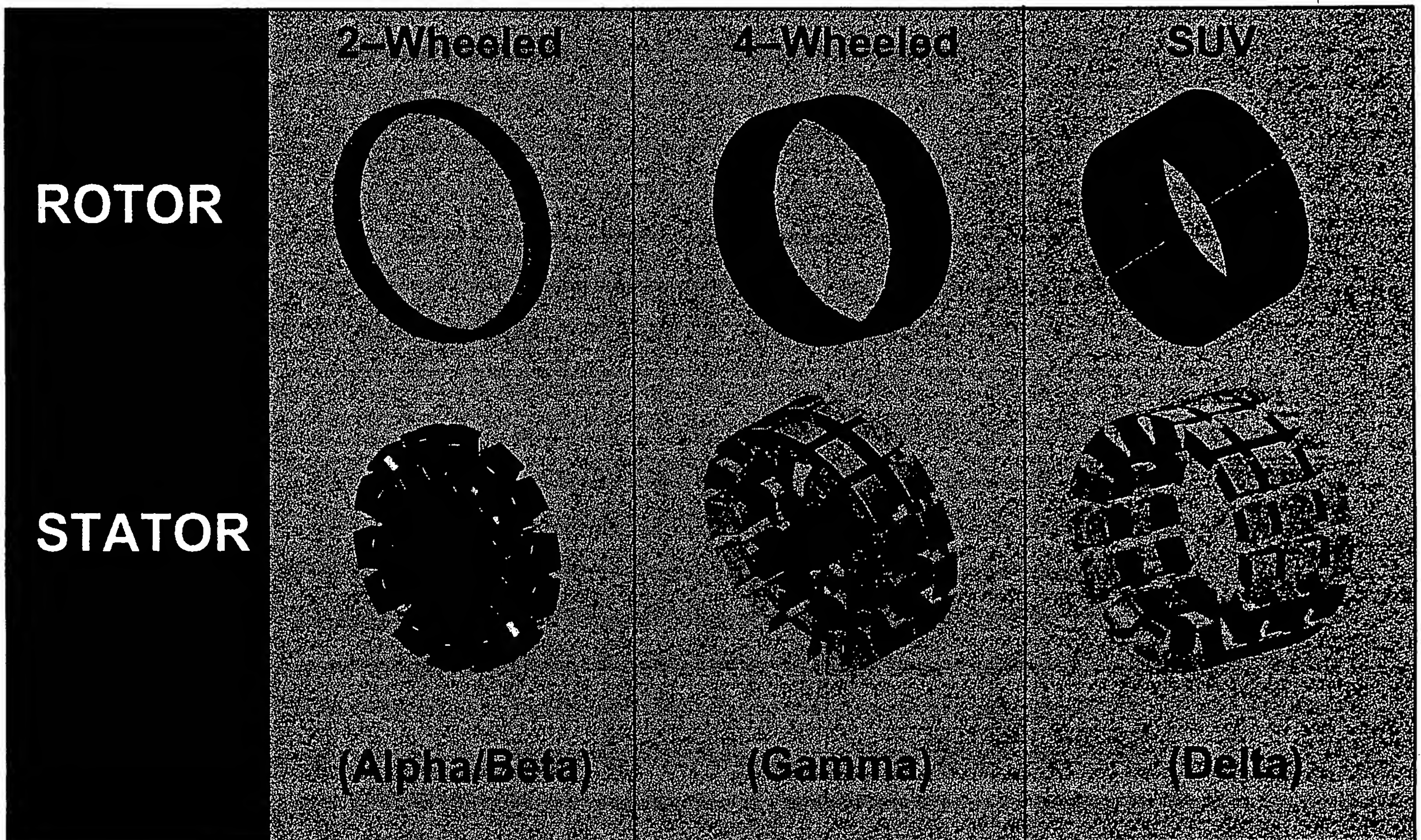

E^n Motor Product Offerings

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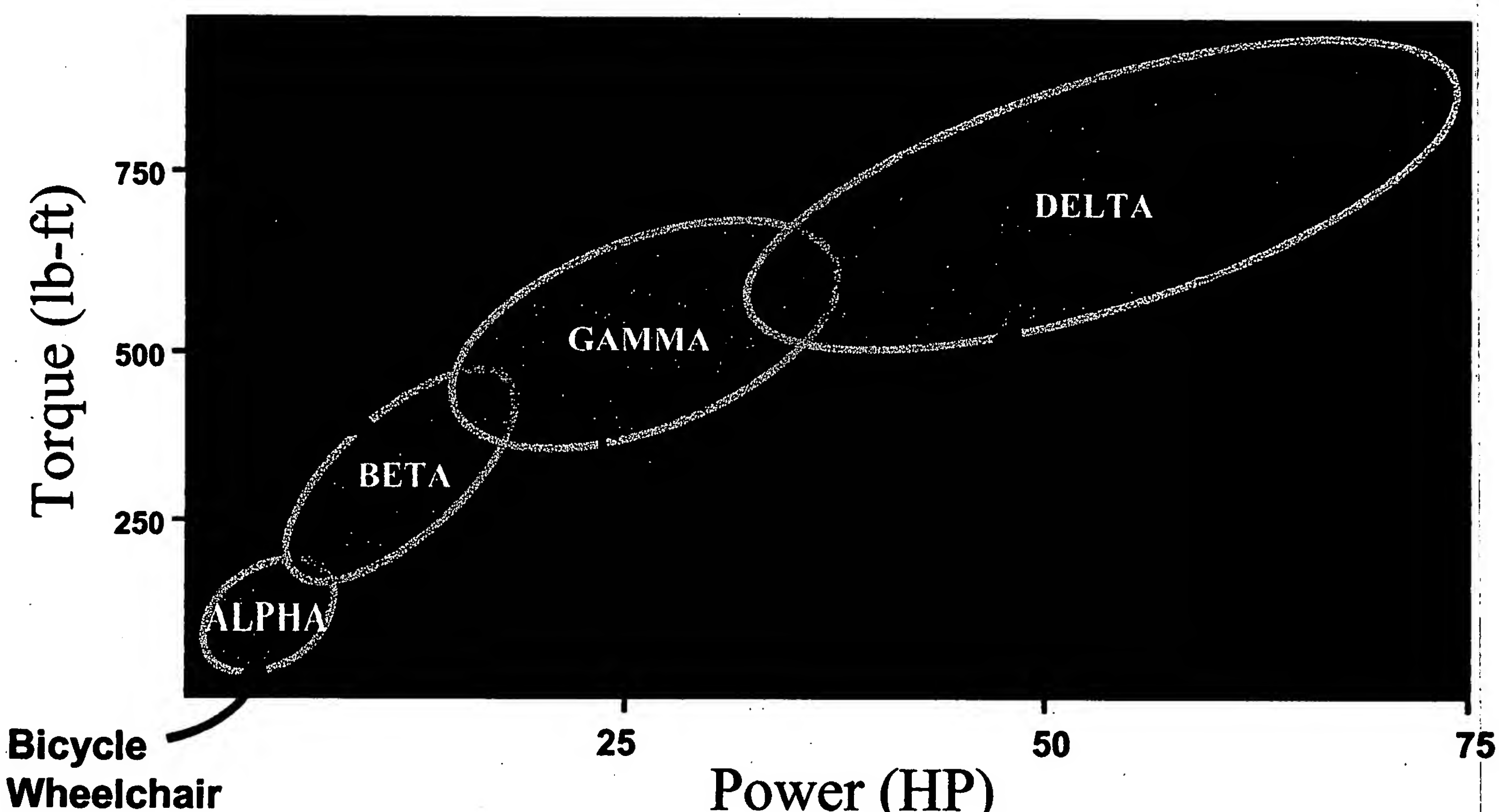
E^n*Power* Motor Product Line



E^n Motor's Unique Advantages

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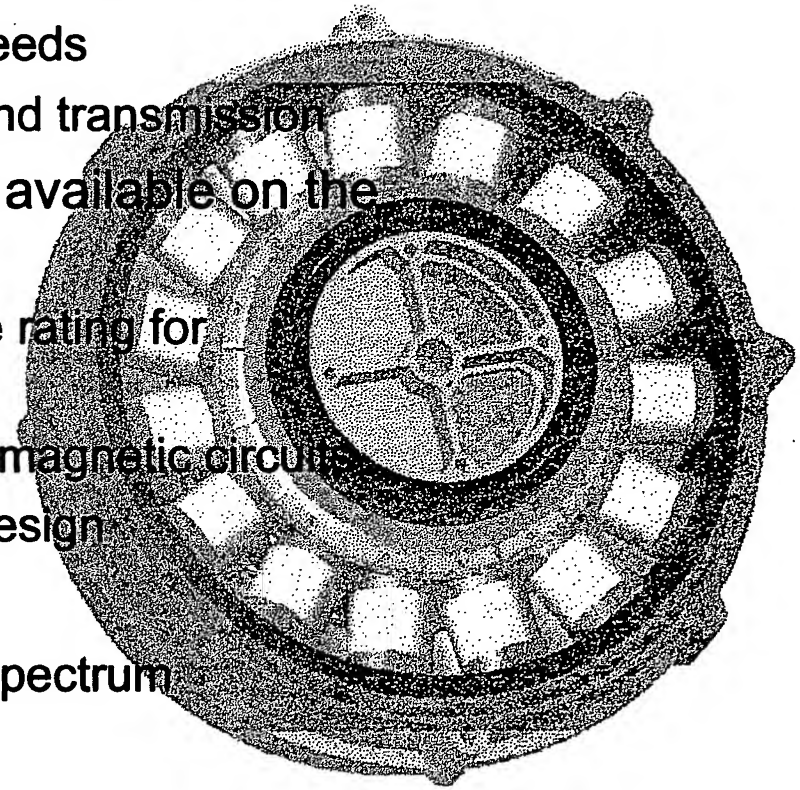

- Total energy management – minimizes conversions
  - Motor delivers high torque at low speeds allowing direct drive without gears and transmission
- Highest torque and power densities available on the market
  - Motor architecture maximizes torque rating for available volume
  - Adaptive control of individual electromagnetic circuits
  - Advanced magnetic materials and design
- High average efficiency

  Optimized across the torque / speed spectrum

E^n Motor's Unique Advantages

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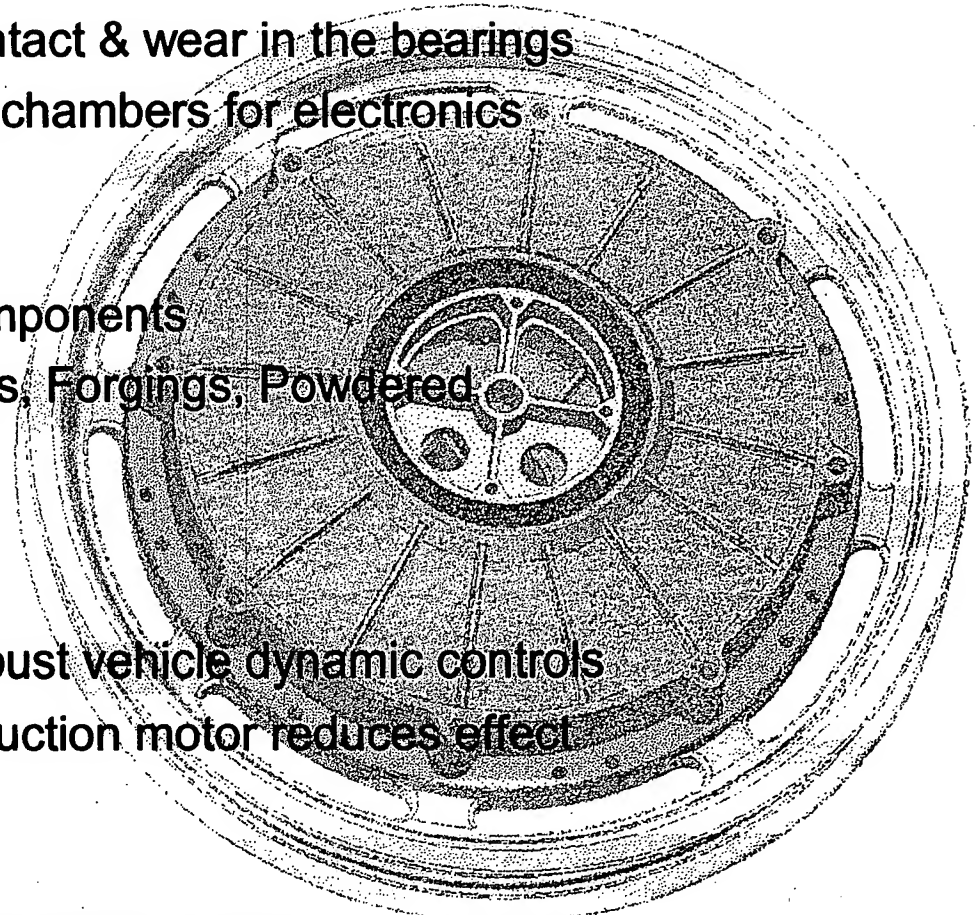

- Reliable
  - Brushless and gearless: only contact & wear in the bearings
  - Forced-air cooling with separate chambers for electronics and electromagnets
- Low cost
  - Flexible: Scalable, Common Components
  - High Manufacturability – Castings, Forgings, Powdered Metals
  - Low Voltage
- Total systems solution
  - Zero speed control allows for robust vehicle dynamic controls
  - Lower speed than typical AC induction motor reduces effect of rotor imbalance
  - Quiet operation minimizes NVH
  - Liquid cooling is optional to boost power output

Design, Simulation and Test Capabilities

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- 3D Solid Modeling
  - SolidWorks® Office
- Finite Element Analysis
  - ANSOFT Maxwell® 3D and SIMPLORER®
    - Electromagnetics
    - Electrical
  - ANSYS MultiPhysics™
    - Structural, Thermal
    - CFD,Acoustics
    - Electromagnetics
    - Coupled Field
- Test & data acquisition system
  - National Instruments LabVIEW™
  - Walker LDJ Scientific

Structural analysis and optimization

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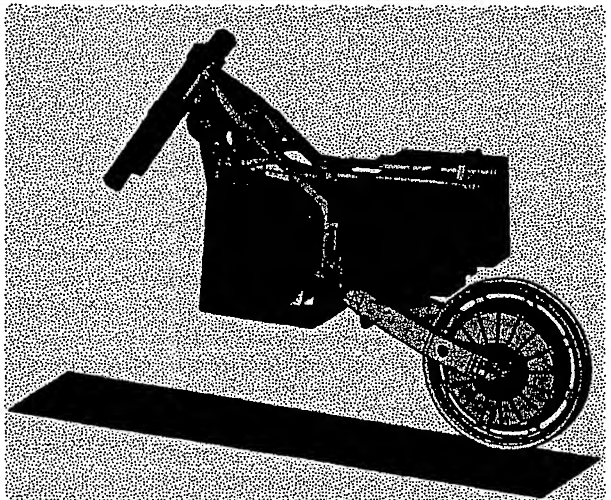

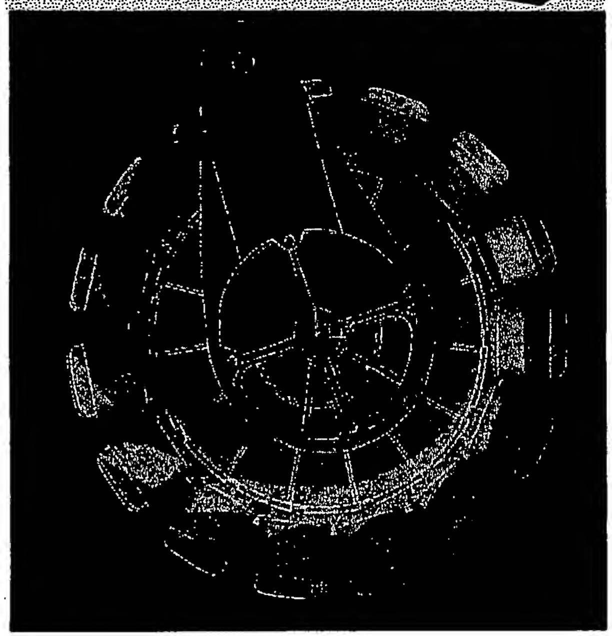

- Static: $\{F\} = [K]\{u\}$
  - Peak acceleration, braking and steering
  - Temperature extremes and variations
  - Non-rotating & fixed angular velocity
- Dynamic : $\{F\} = [K]\{u\}+[C]\{\acute{u}\}+[M]\{\ddot{u}\}$
  - Modal analysis for natural frequencies and corresponding mode shapes
  - Harmonic Analysis—magnetic forces, rotor imbalance, road and random vibrations
  - Transient Dynamic Analysis—shock loading
- Nonlinear
  - Material properties
  - Loading
  - Response

Thermal Design

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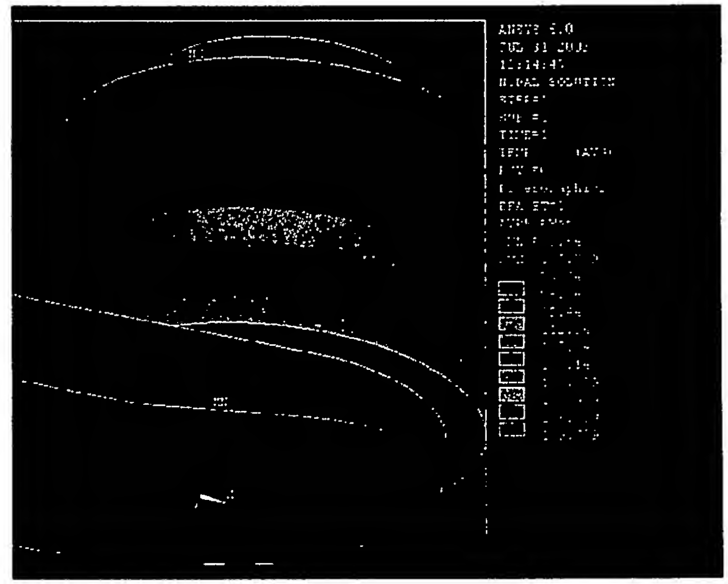
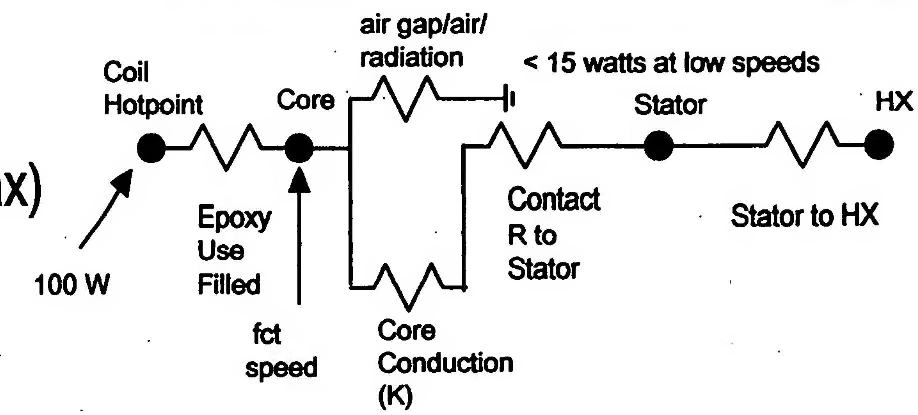
- Thermal analysis and optimization
  - Finite Element Analysis
  - Lumped Model Analysis
- Heat sources
  - Active losses
    - Copper ($I^2 R$)
    - Electronics (conduction and switching)
  - Passive losses
    - Hysteresis ($\sim f$)
    - Eddy currents ($\sim f^2$)
    - Controls & Sensors
  - Solar radiation (1.4 kW/m^2 max)
- Critical temperatures
  - Outside air ($T_0 \leq 40\,°C$)
  - Components and materials





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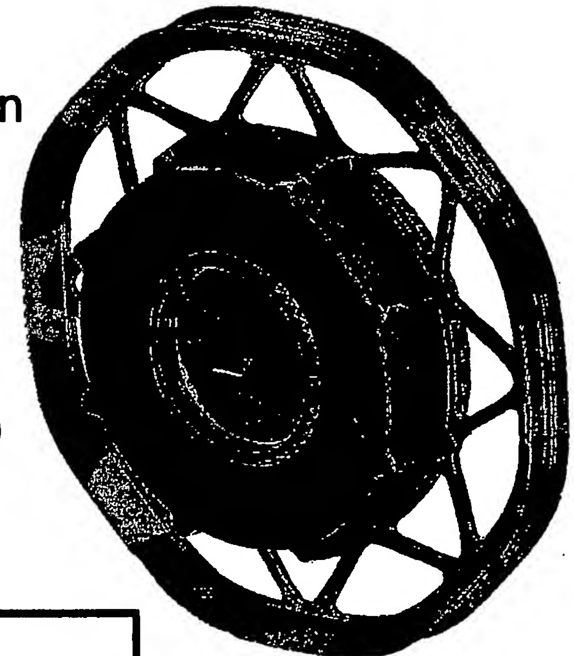
Mechanical & Thermal Optimization

- Maximize torque density while controlling vibration and noise through structural FEA optimization of complete motor structure
  - Current: 21.7 Nm/kg (Gamma)
  - Goal: 25+ Nm/kg
- Maximize power density using thermal FEA, CFD and lumped thermal circuit analysis



Cooling Method	Current Designs	Goal
Passive	Po < 1600 kW/m^3	2000+ kW/m^3
Forced Air	1600 < Po < 2500 kW/m^3	3000+ kW/m^3
Forced Liquid	Po > 2500 kW/m^3	

Magnetic Design Parameters

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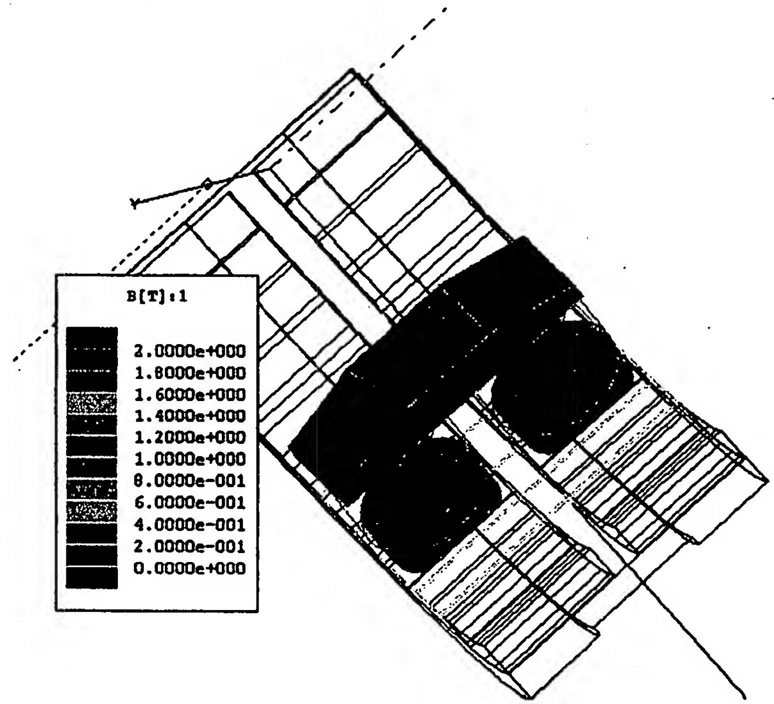
- High torque density design
  - High energy materials
  - Reduction of active weight
  - Design topology and architecture
  - Considerations for: K_e,K_T and K_m
  - Improved form factor
- Optimize Average Efficiency
  - Low loss material selection
  - Low torque ripple and cogging
  - Effective winding technology
- Reliable Design
  - Adequate thermal management
  - Thermal stability
  - No structural degradation
- Low cost
- 3D simulation and synthesis



Motor Architecture

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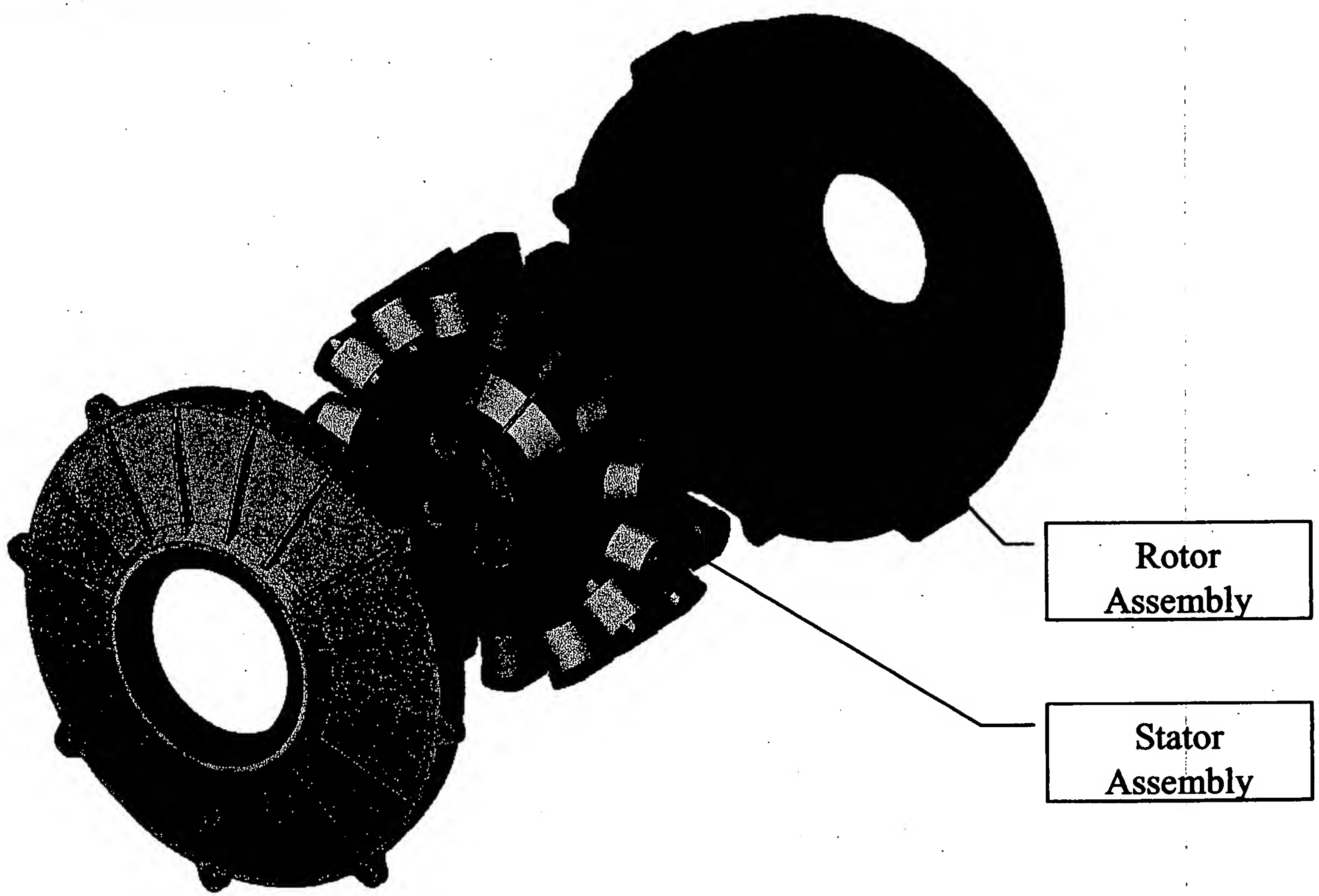

Loss Optimization

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Losses Reduced in E^nPower Motor

- Copper
  - Ohmic and inductive losses in the stator winding
- Core (sinusoidal and non –sinusoidal)
  - Hysteresis
  - Eddy current
  - Anomalous
  - Harmonic
- Irreversible in PM Rotor
  - Due to pulsating flux caused by change in reluctance
  - Eddy current losses in the PM bulk and surface layers as a function of field switching

- Other losses considered
  - Switching
  - Stray
  - Rotational or Mechanical
  - Windage

High Torque Per Unit Volume

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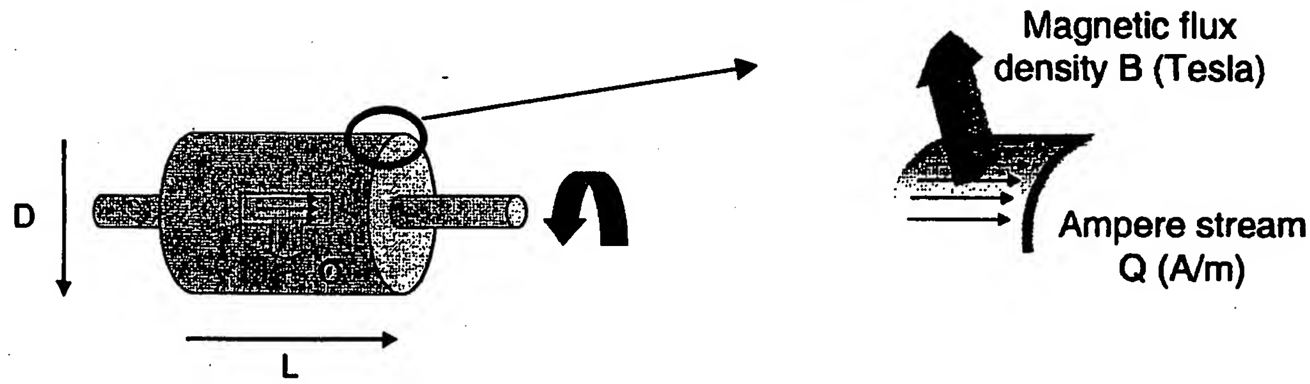

Sheer stress $\sigma = ku.B.Q$ ➡ Torque $= \pi/2.D^2.L.ku.B.Q$

Active Volume = $\pi/4.D^2.L$

Ku := Factor which relates to the practical realization of the magnetic field and the current sheet

B := Average air-gap flux density, limited by the max. working flux densities of stator/ rotor constituents

Q:= Electrical loading, which is total ampere stream per meter of air-gap circumference. This is limited by ability to dissipate copper winding loss

Air Gap Flux Density => High Torque

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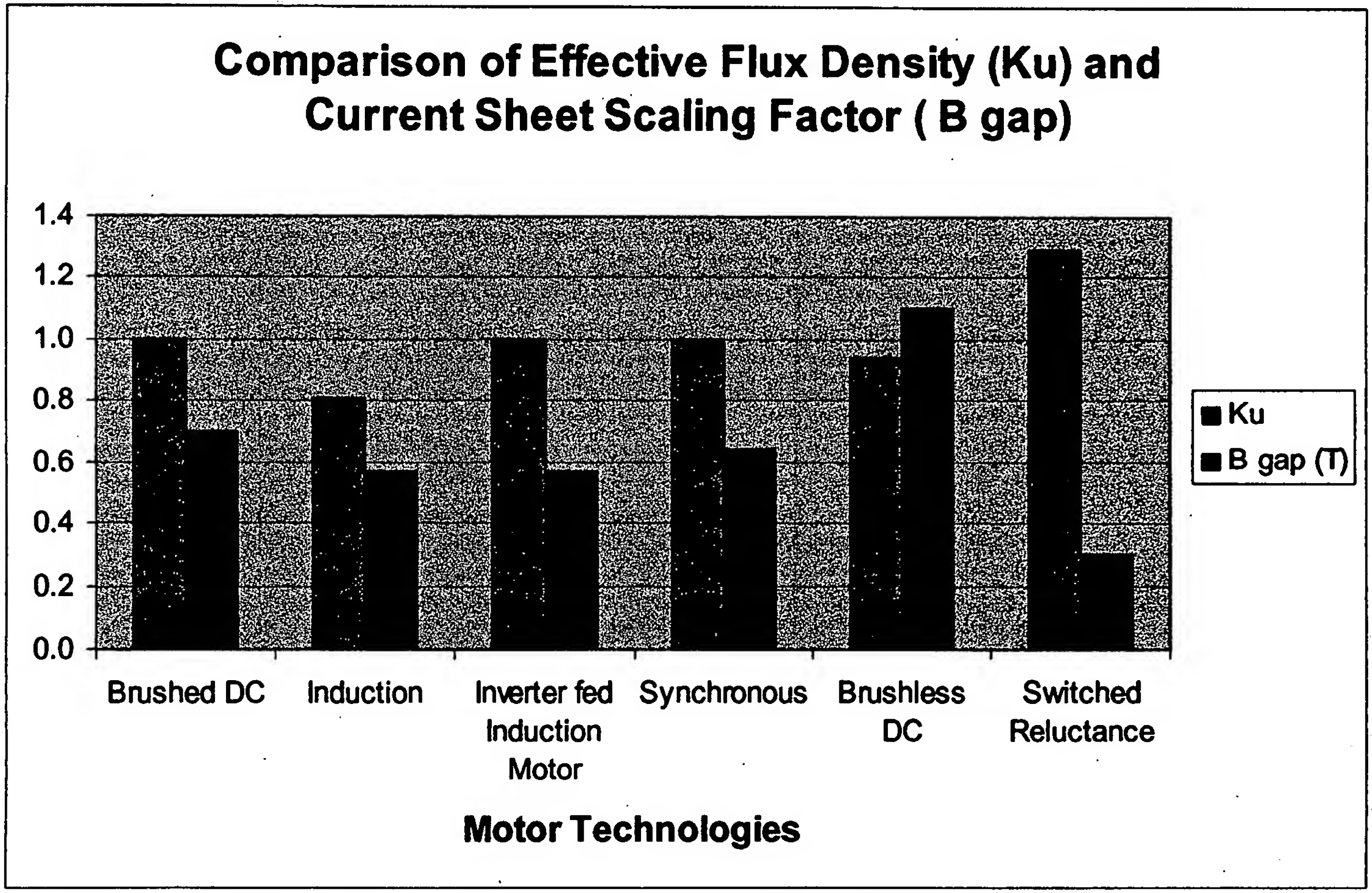

IEE Power Division Colloquium, London, UK, 1993/80

High Sheer Stress => High Torque

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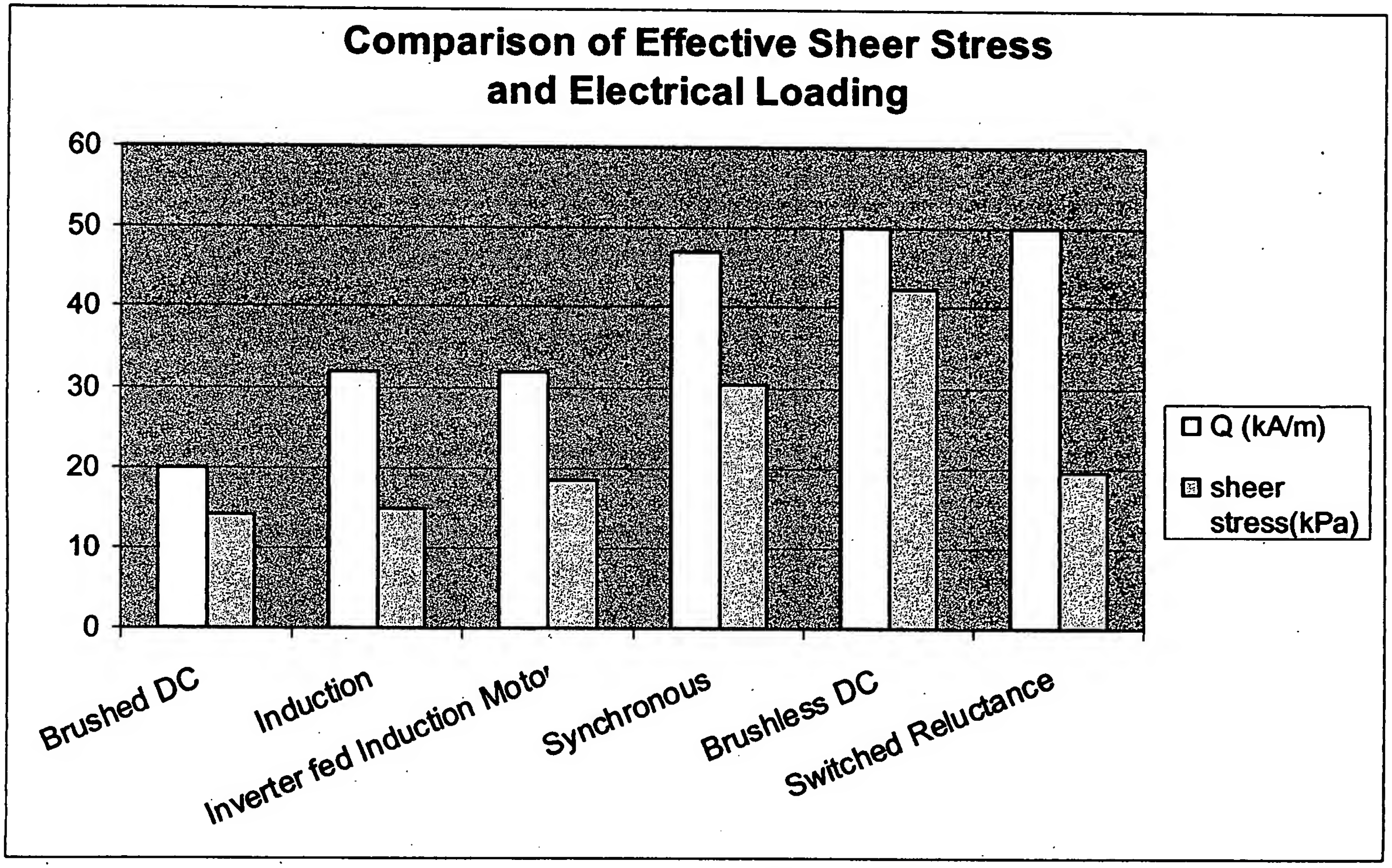

IEE Power Division Colloquium, London, UK, 1993/80

Soft Magnetic Composite Materials

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- Innovative isotropic powder matrix
  - Insulated grains (via resin bonding agent or oxide layer)
  - Extremely high electrical resistivity vs. best high-silicon steels (1000 vs. 40 to 50 μohm cm)
  - Very low eddy current loss at application frequencies and magnetic flux densities
- High compaction pressure induces residual strains in the powder matrix
  - Results in slightly higher hysteresis losses that are proportional to the frequency
  - Eddy current loss proportional with the square of the frequency
  - Lower total core loss vs. laminated materials at high frequencies and key induction levels

Advanced Material Science => Form Factor

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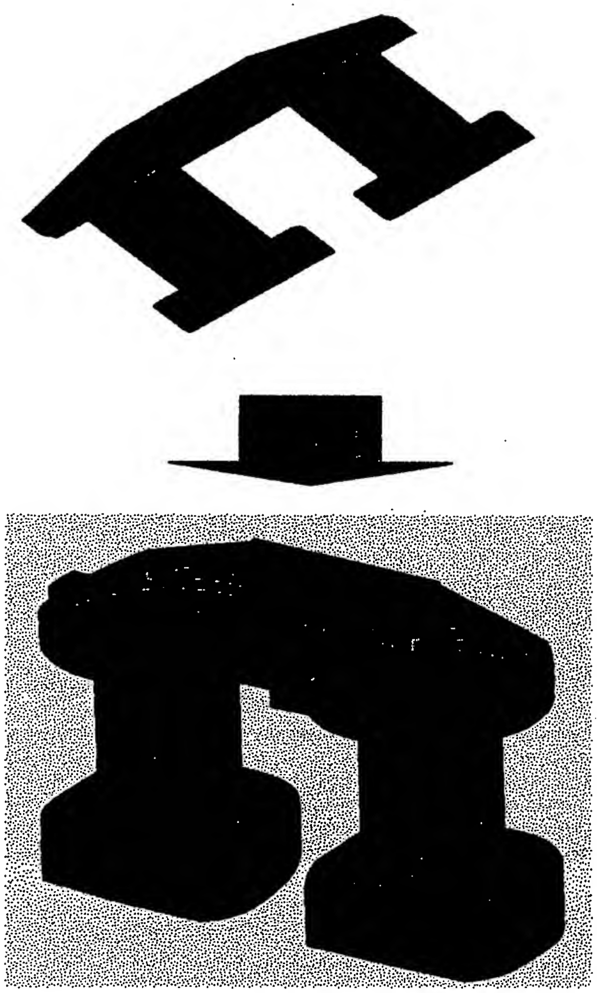
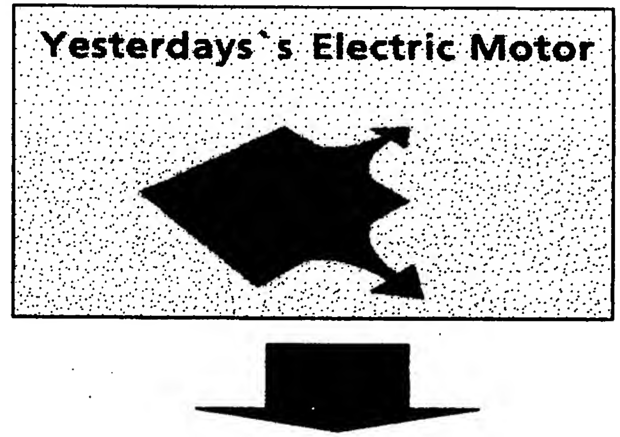
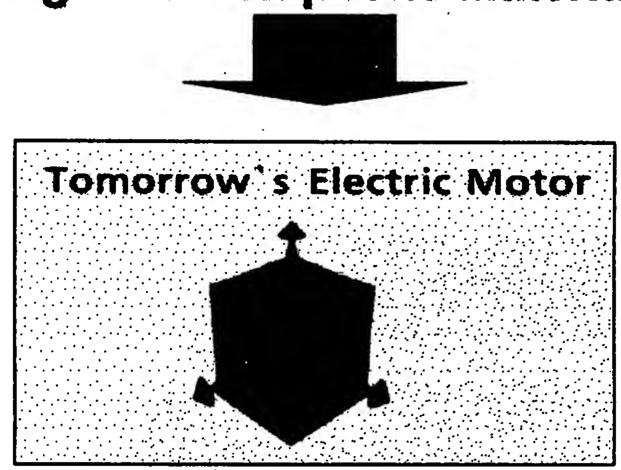




Soft Magnetic Composite Materials



Soft Magnetic Composite Materials

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- Magnetic properties can be adjusted for:
  - High saturation
  - Adequate operating permeability
  - Reduced core loss for light weight applications
- Possible grade options:
  - Fe (pure gas atomized Iron)
  - Si-Fe (3% Silicon Iron)
  - Si-Fe-Co (3% Silicon Iron 0.45% Cobalt)
  - Si-Fe-P (Silicon Iron Phosphorous)

The Advantages of the Core Design

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- Designed to minimize weight
  - SMC allows electrical machine component construction with 3D magnetic fields
  - Permeability and the saturation levels compromised by the density variations and heat treatment of the material
- Designed to optimize power and torque density
  - Increases design flexibility
  - Increases specific output
  - Better thermal and acoustic management at operating frequencies
- Designed to maximize average efficiency
  - Lowers flux leakages resulting in lower stray low impedance electromagnetic signature
  - Improves component form factor which promotes better packing factor for coil winding (typically 80 to 85%)

Rotor Material Selection

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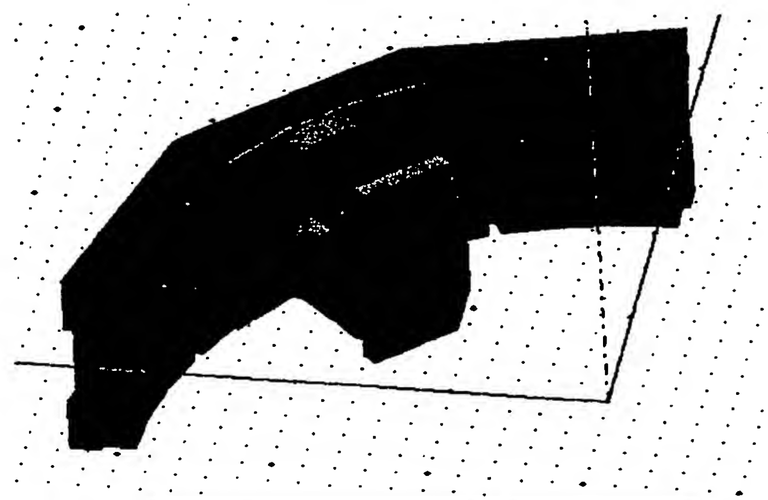
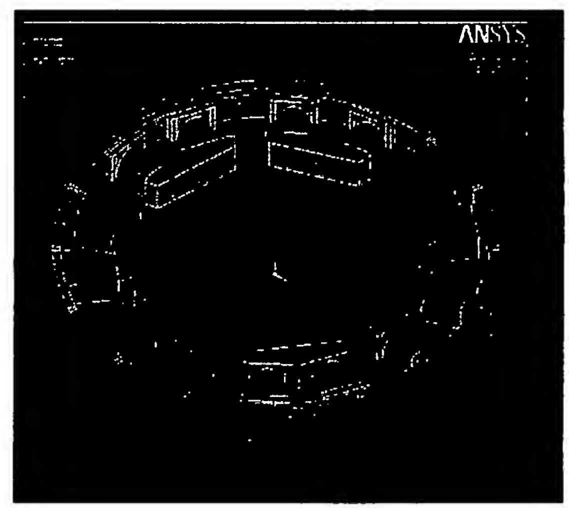
- NdFeB
  - Operating temperatures up to 220°C
  - Highest energy products
  - High temperature stability
  - Requires surface coating
- SmCo5 and Sm2Co17
  - Operating temperatures up to 350°C
  - Highest temperature stability
  - Very low temperature dependence
  - High corrosion resistance





Rotor Design Advantages

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- Conventional high BHmax magnets
  - Typical BHmax or energy product of 30 to 50MGOe (238 to 398 kJ/m3)
  - Option to configure in single or double spaced axial with solid or laminated back iron
- Designed to minimize weight
  - Segmented back iron
  - Hallbach magnet arrays
- Designed to optimize magnetic performance
  - Shaped in rounded square sectors with special tapered edges to minimize cross interference of unwanted magnetic flux
  - Radially magnetized to provide strong magnetic polarizations perpendicular to the plane of the back iron ring for each partitioned section of the rotor
  - Optimized to adjust the permeance, the optimum working point, and the recoil characteristics of the magnet subsystem with controlled irreversible losses
- Designed surface coating and pattern to reduce surface eddy current losses of the magnet segments

Design Cycle and Synthesis

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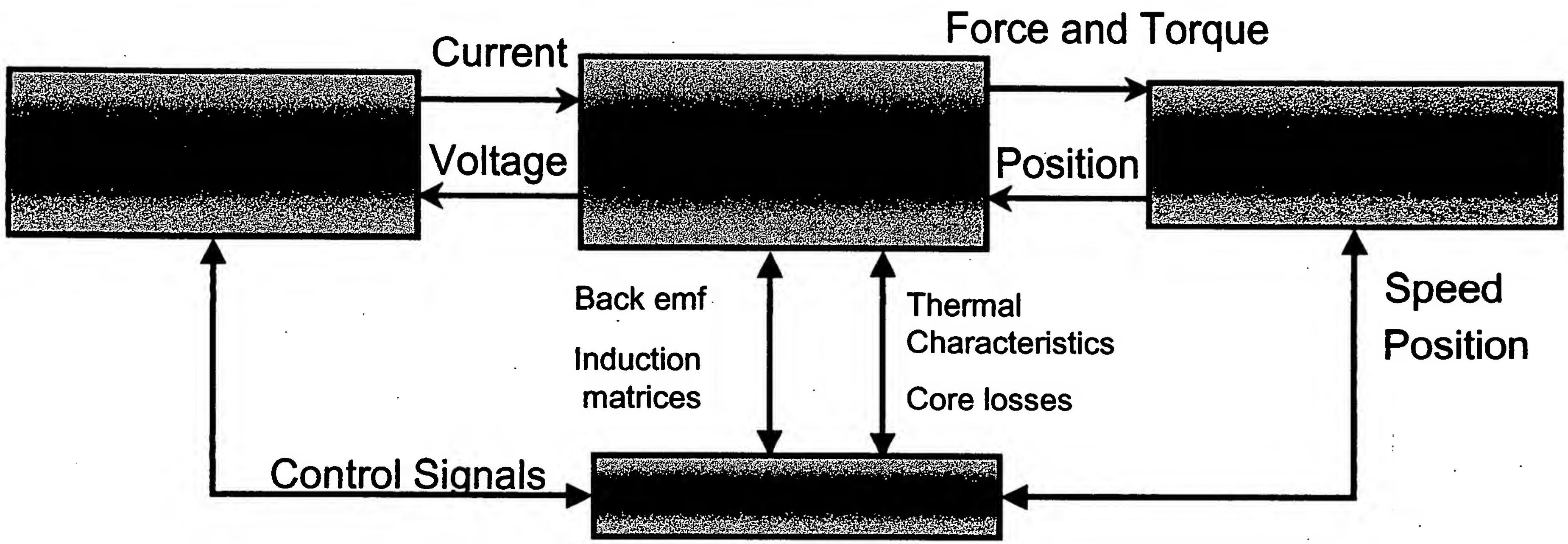

- At WaveCrest we carry out virtual design synthesis of the motor for different engineering areas in order to reduce the development cycle. This enables us to model the motor completely prior to building a prototype
- We use advanced multi-disciplinary packages to simulate 3D simulations in key engineering areas such as: - Electromagnetic, -Mechanics, -CFD thermal, -Power electronics, -Controls

Animated Simulation of Gamma

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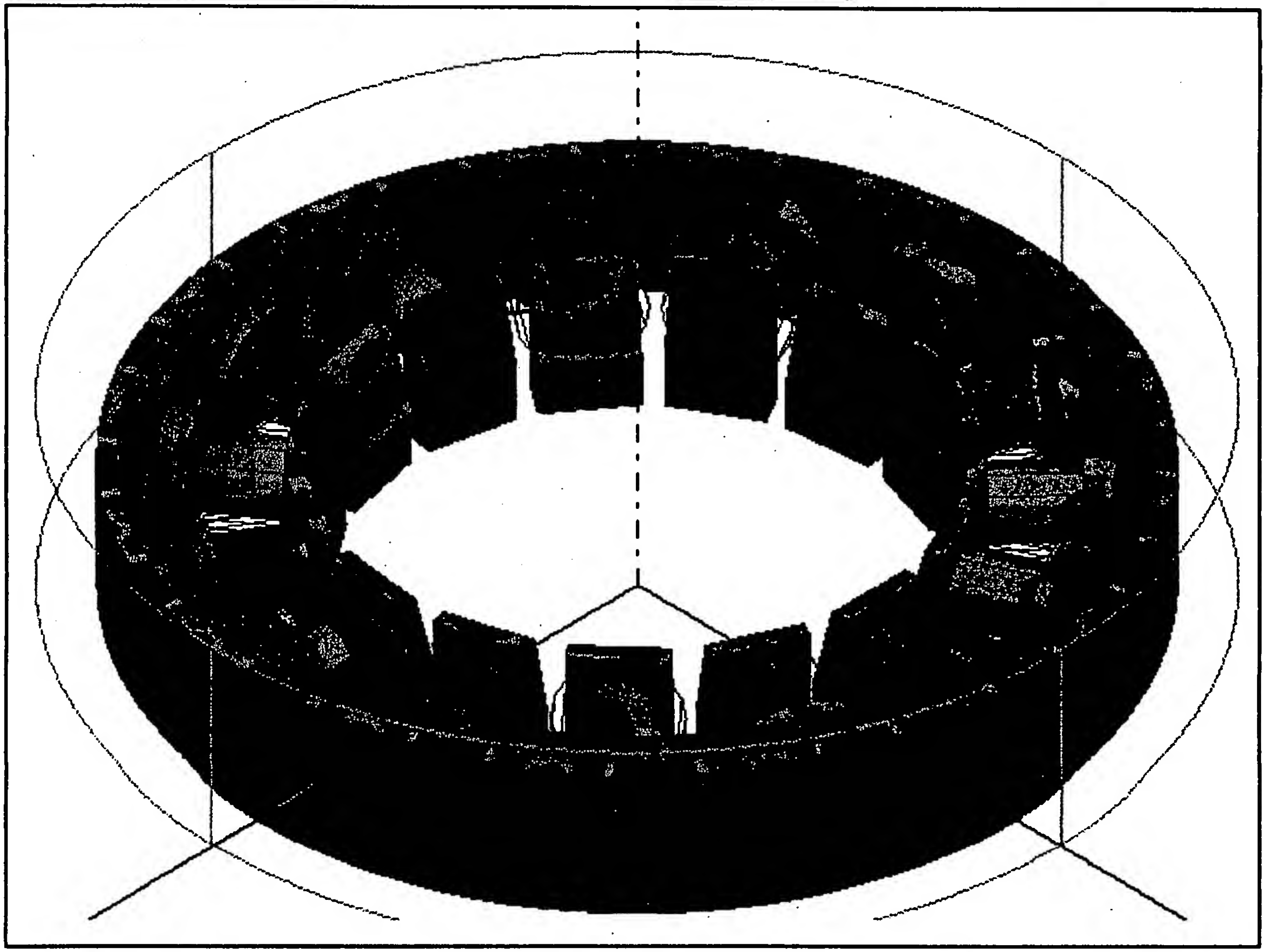

FEA and Test Comparison of the Torque

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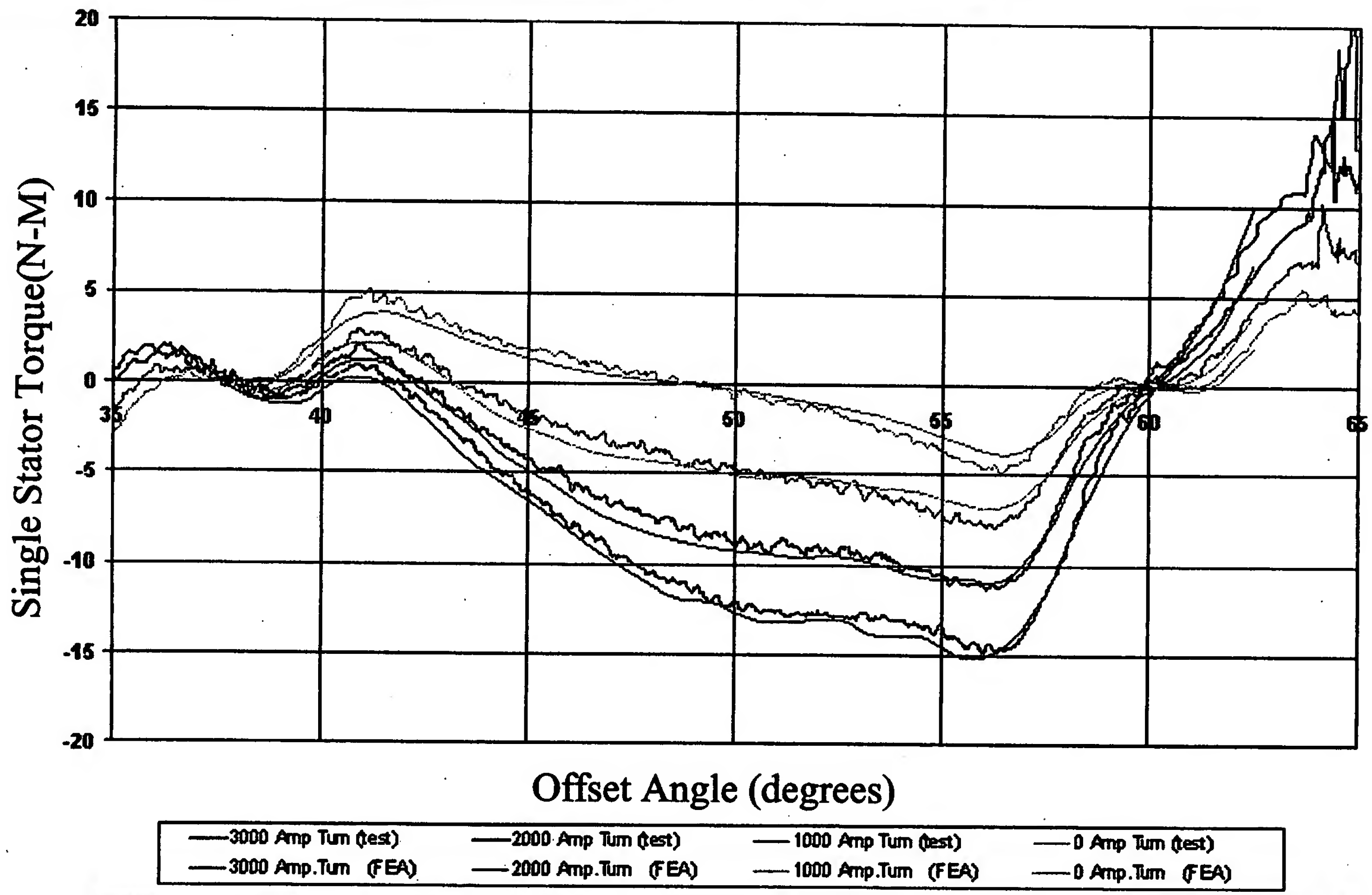

The correlation of the simulated and measured torque performance of the design under different current loading and angular positions

Electromagnetic Compatibility

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Key subjects examined during EMC (Electromagnetic Compatibility) pre-compliance and formal approval tests:

- Electrostatic discharge test
- Conducted immunity /interference tests (150kHz to 300MHz)
- Radiated immunity /interference tests (300MHz to 1GHz)
- Emissions test
- Supply, emitted voltage surges
- Emitted voltage transients
- Line frequency (50/ 60Hz) field magnetic susceptibility
- Pulsed magnetic field susceptibility
- Oscillatory magnetic susceptibility
- Supply dips and voltage interrupts

subcategories according to EN5024 and EN61000-4 standards

Controls Design Objectives

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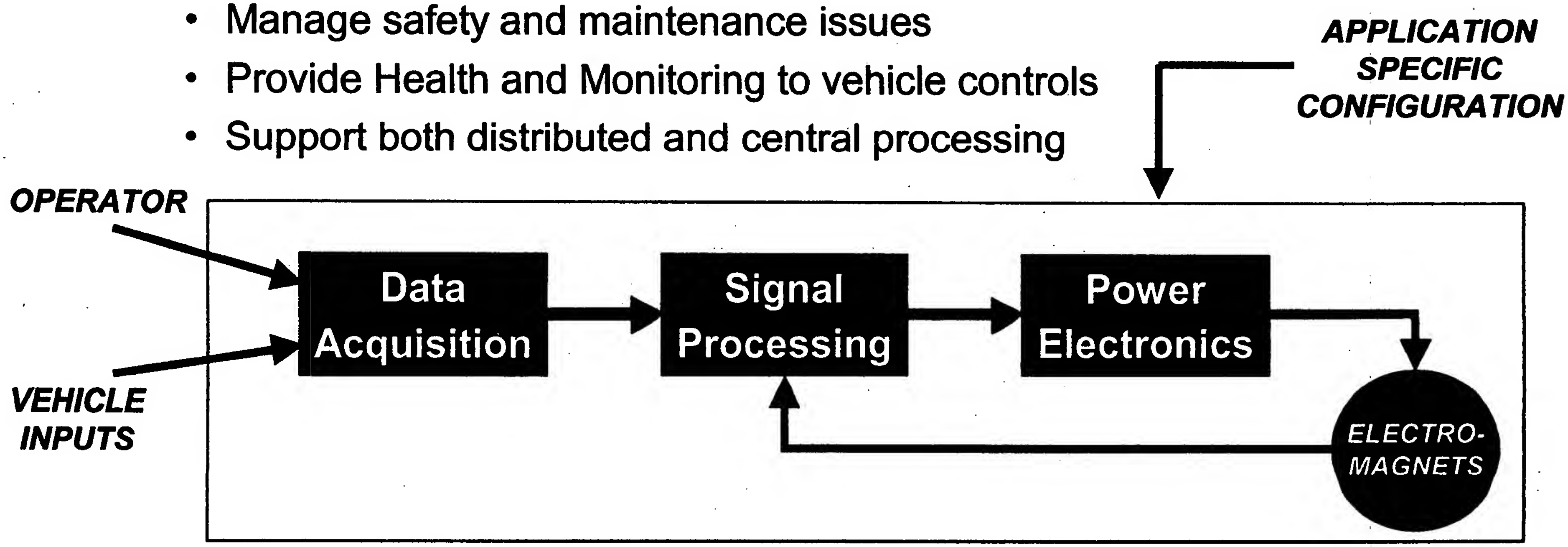
GOALS

- To optimize & maximize motor performance
- Standardize across vehicle applications
- Flexible to be customized to specific application
- Dynamically configurable to adapt to variations in operating conditions
- Trade-off complexity, cost and size
- Manage safety and maintenance issues
- Provide Health and Monitoring to vehicle controls
- Support both distributed and central processing



Control Design Strategy

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- Support dynamic performance and conditions
  - Five levels of Flexibility
    - By **DESIGN** default ← *PHYSICAL*
    - At the **FACTORY**
    - By the **USER** ← *PROGRAMMABLE*
    - Based on **MOTOR** conditions
    - Based on **VEHICLE** conditions ← *DYNAMIC*
  - Five levels of Performance
    - **FUNCTIONAL REQUIREMENTS** (Torque, speed, power, …)
    - **PERFORMANCE QUALITY** (Torque ripple, Top speed, , …)
    - **SYSTEM EFFICIENCY** (Motor, Controls, power distribution, …)
    - **SYSTEM SAFETY** (Fault diagnostics, operating limits, …)
    - **FAULT TOLERANCE** (redundancy, performance monitoring, …)

Control Design Roadmap

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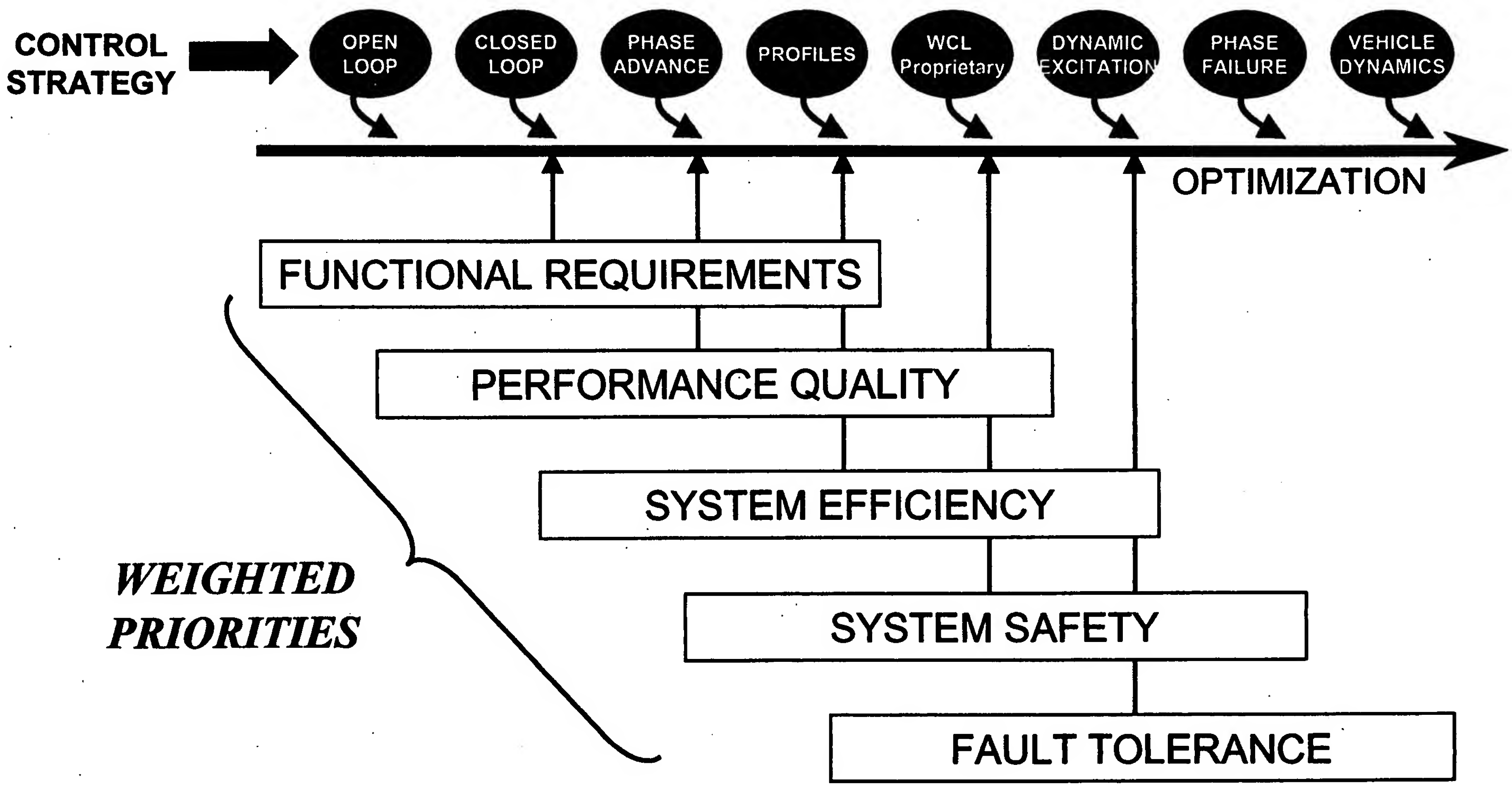
- Adaptive Controls Design



CONTROLLABILITY

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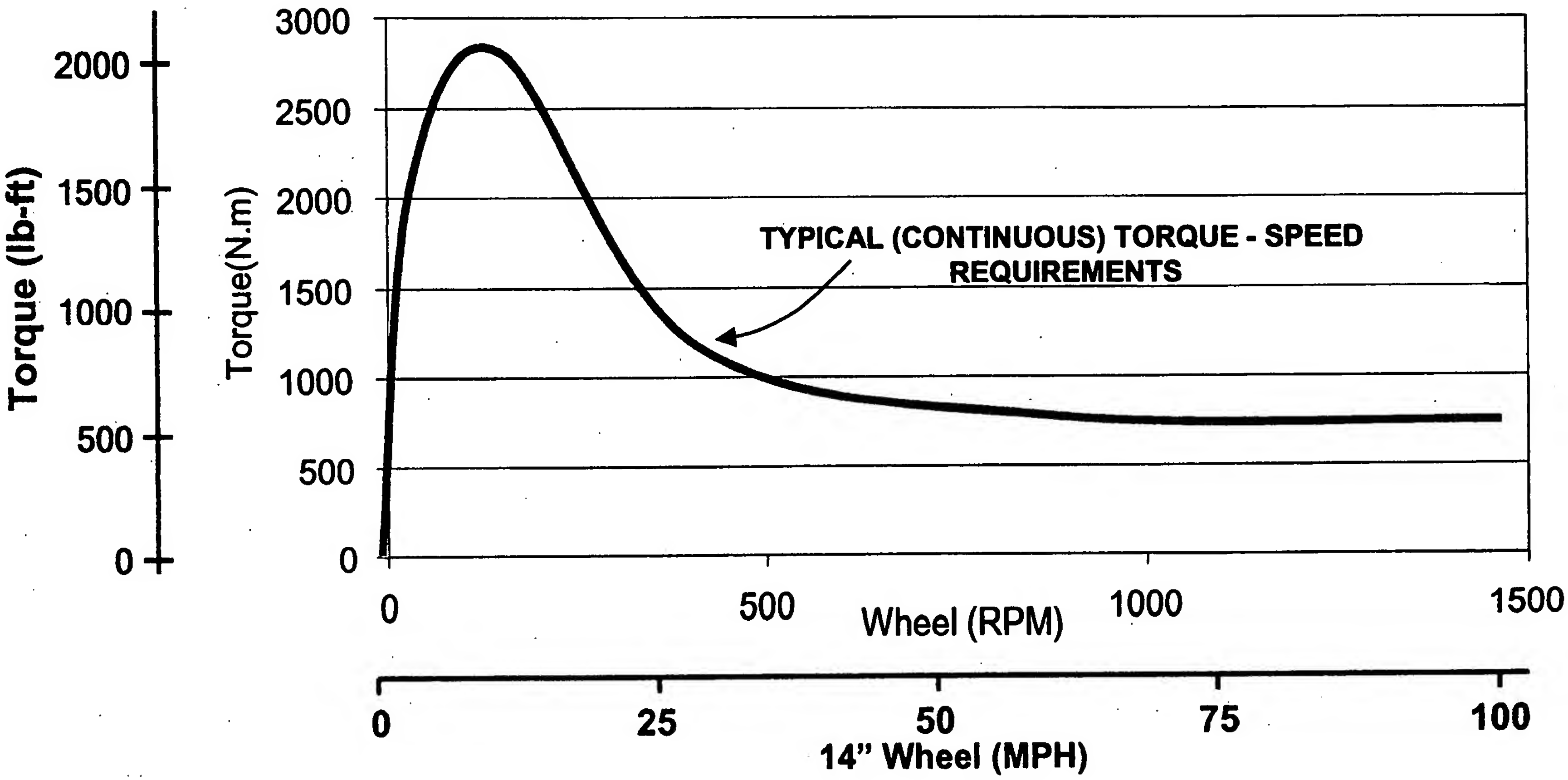
- Motor Torque-Speed Performance (In-wheel)



CONTROLLABILITY

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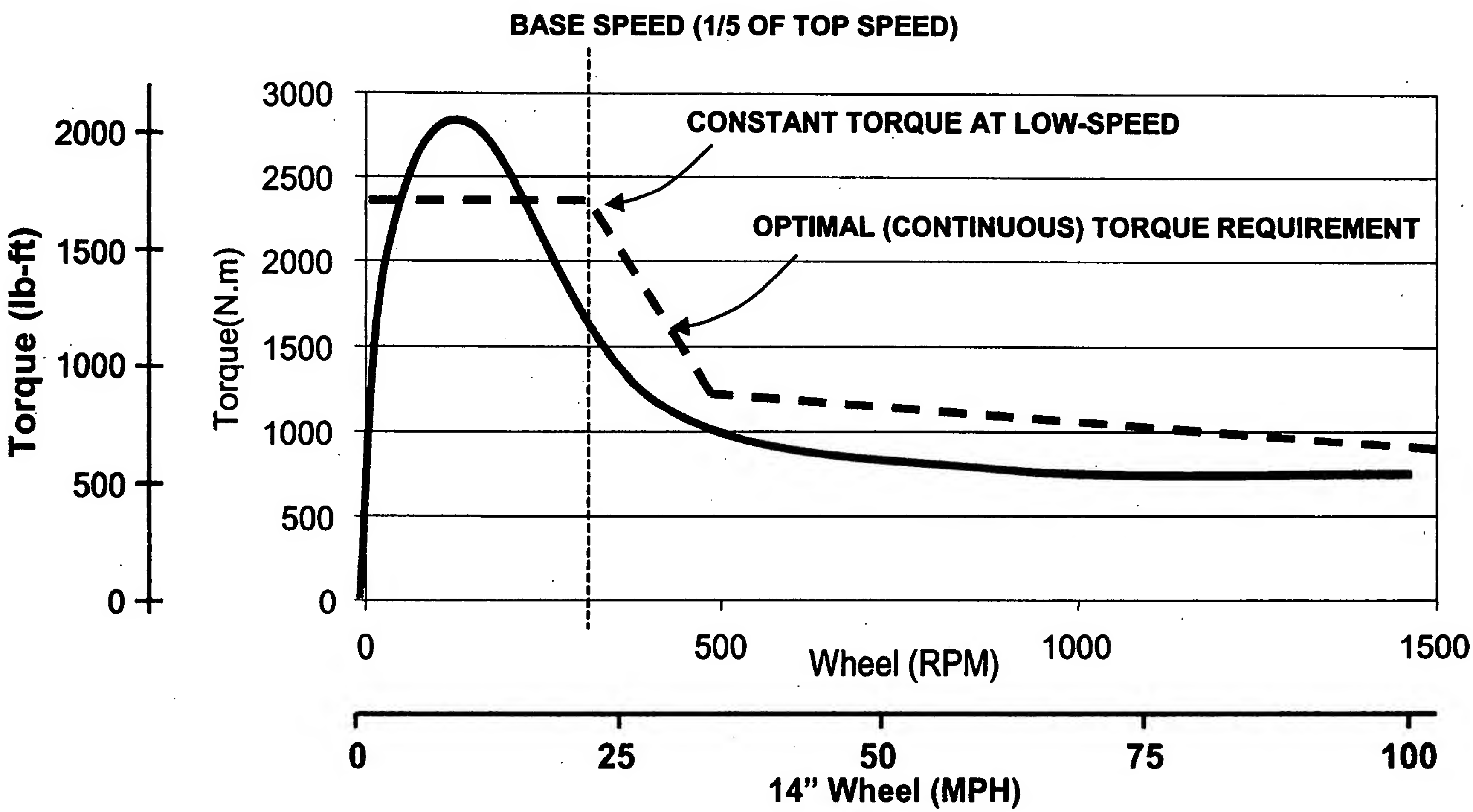
- Motor Torque-Speed Performance (In-wheel)



CONTROLLABILITY

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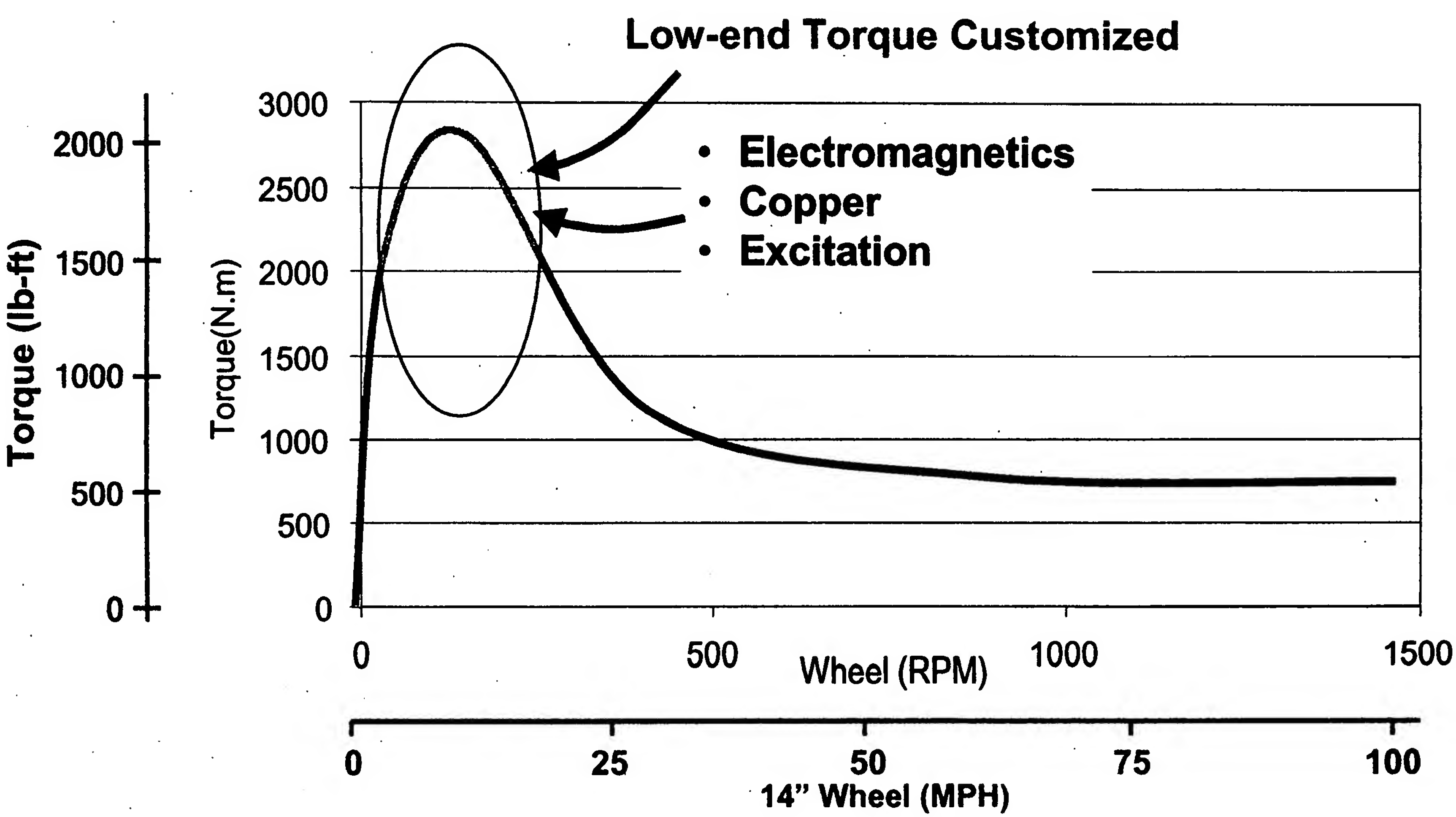

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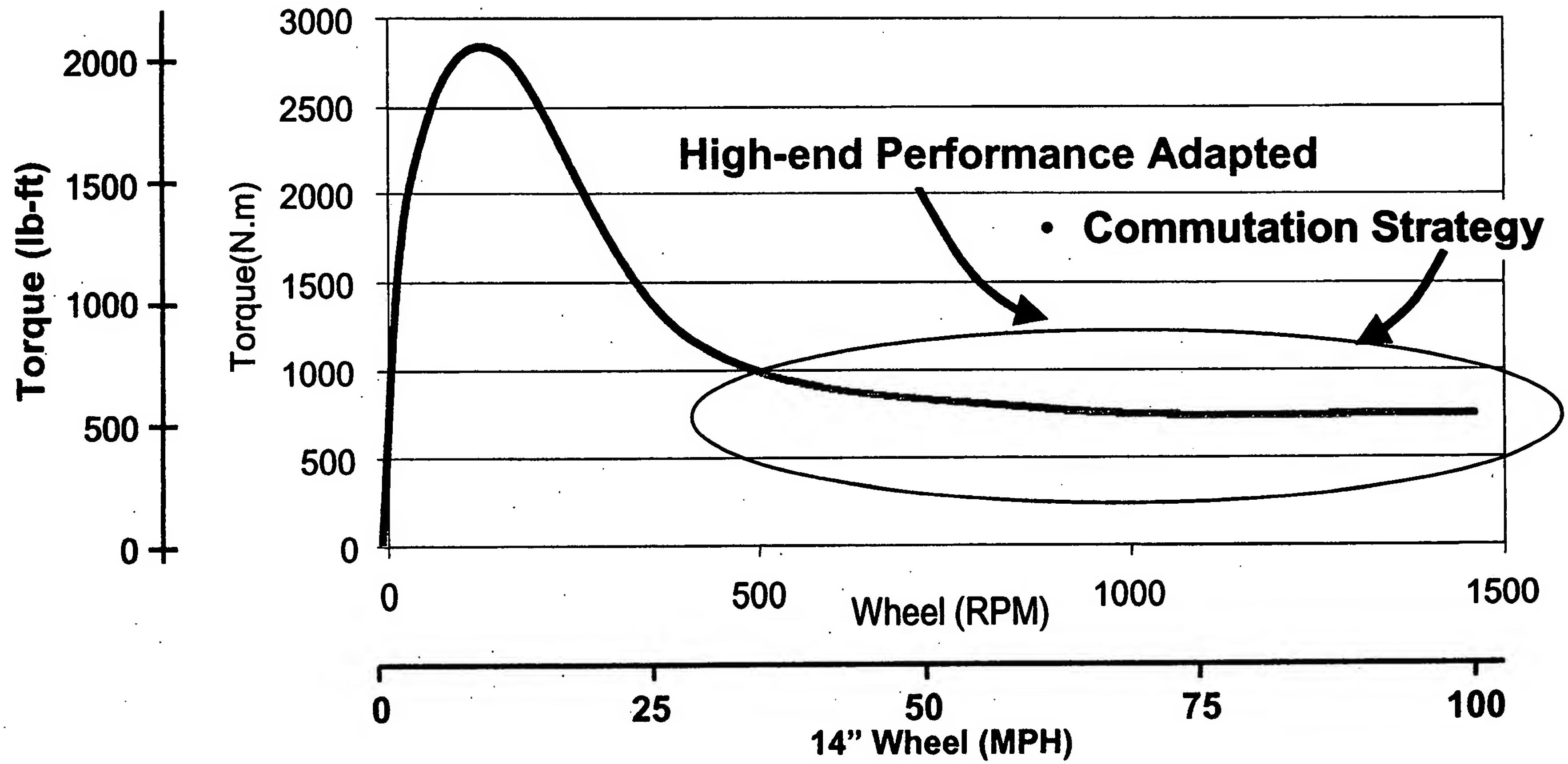
CONTROLLABILITY

- Motor Torque-Speed Performance (In-wheel)



CONTROLLABILITY

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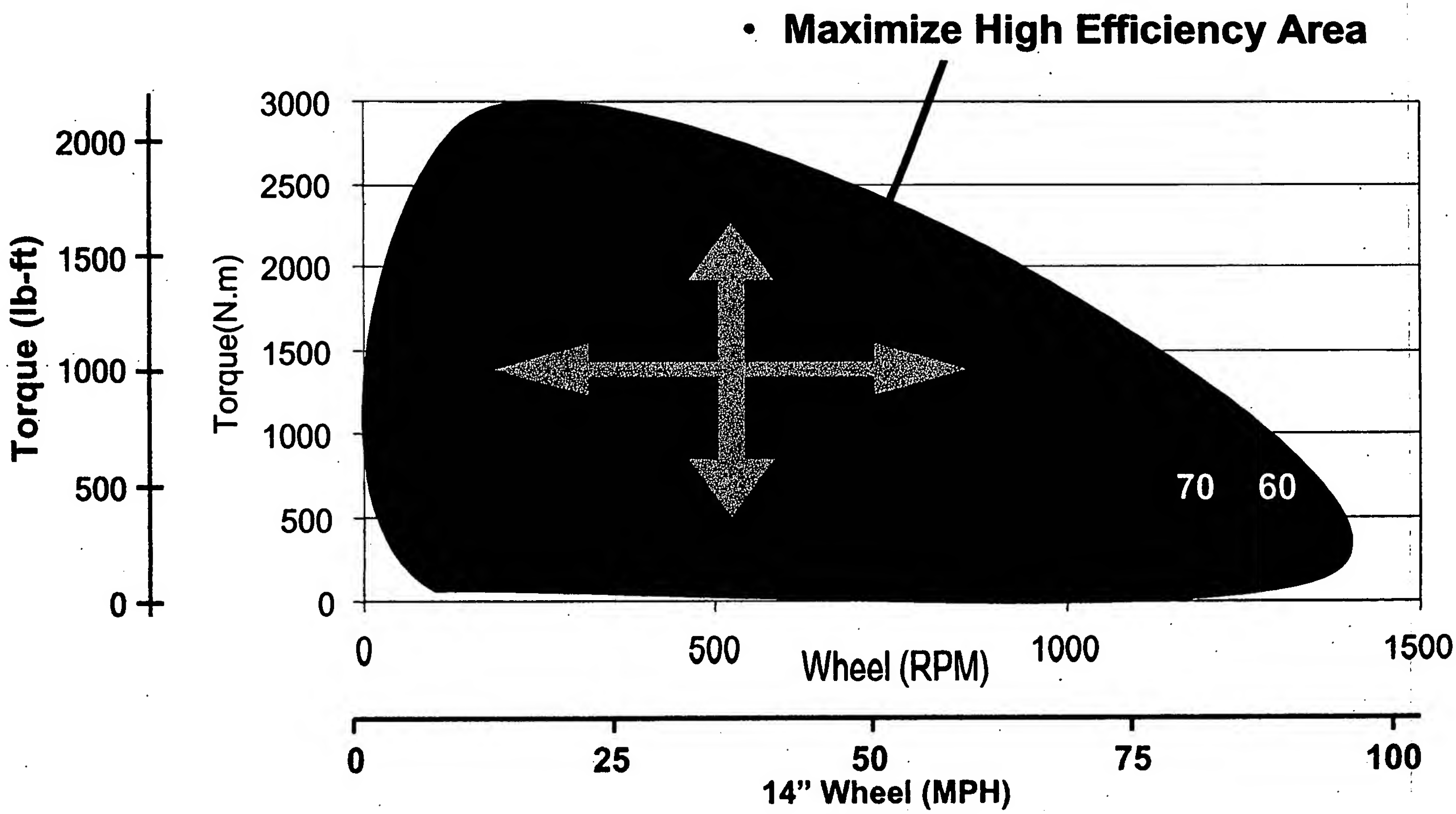
- Motor Efficiency (%)



CONTROLLABILITY

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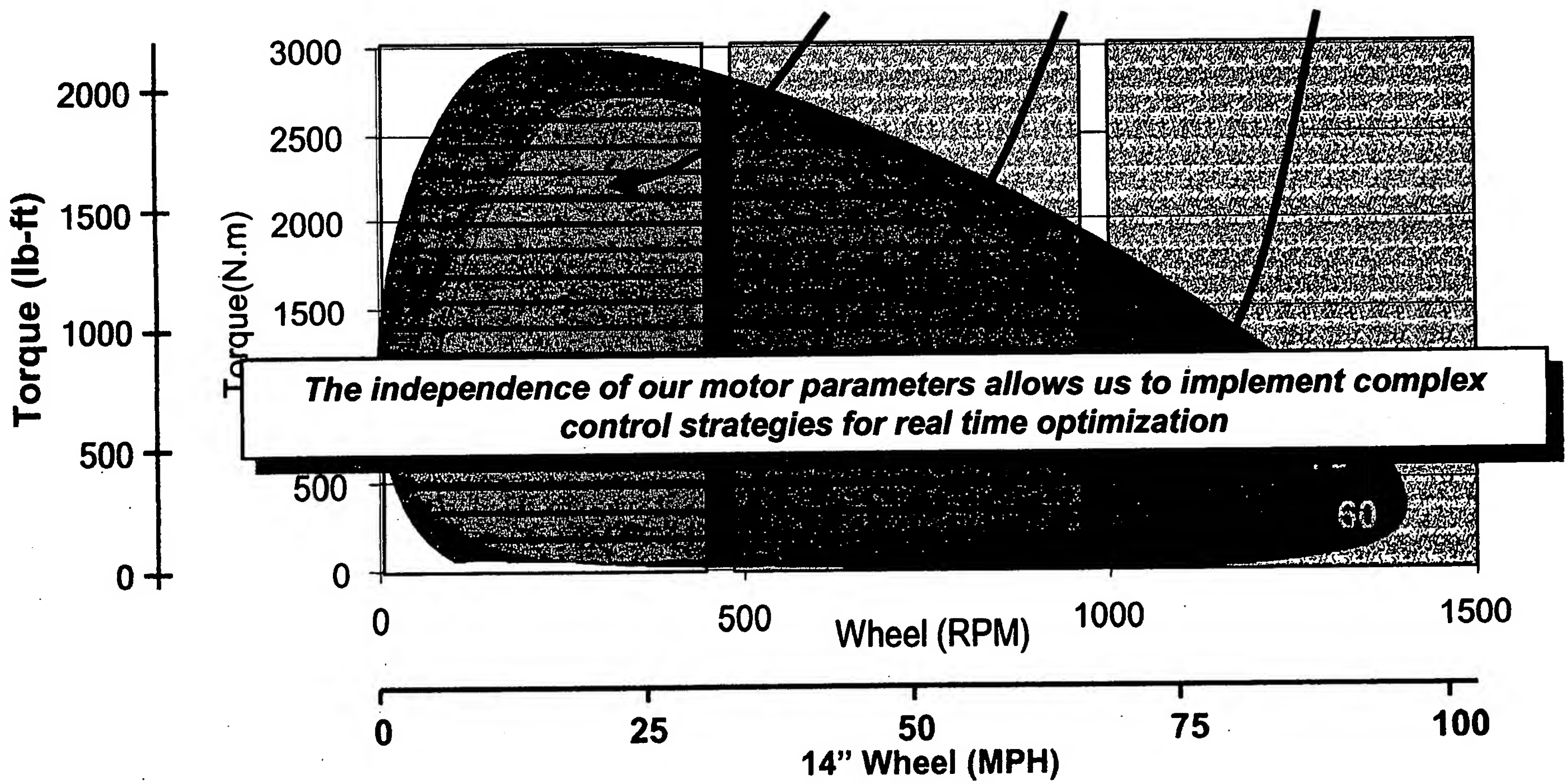
- Optimized to maximize efficiency
  - **Multiple Control Strategies may be implemented**



Control Hardware Design

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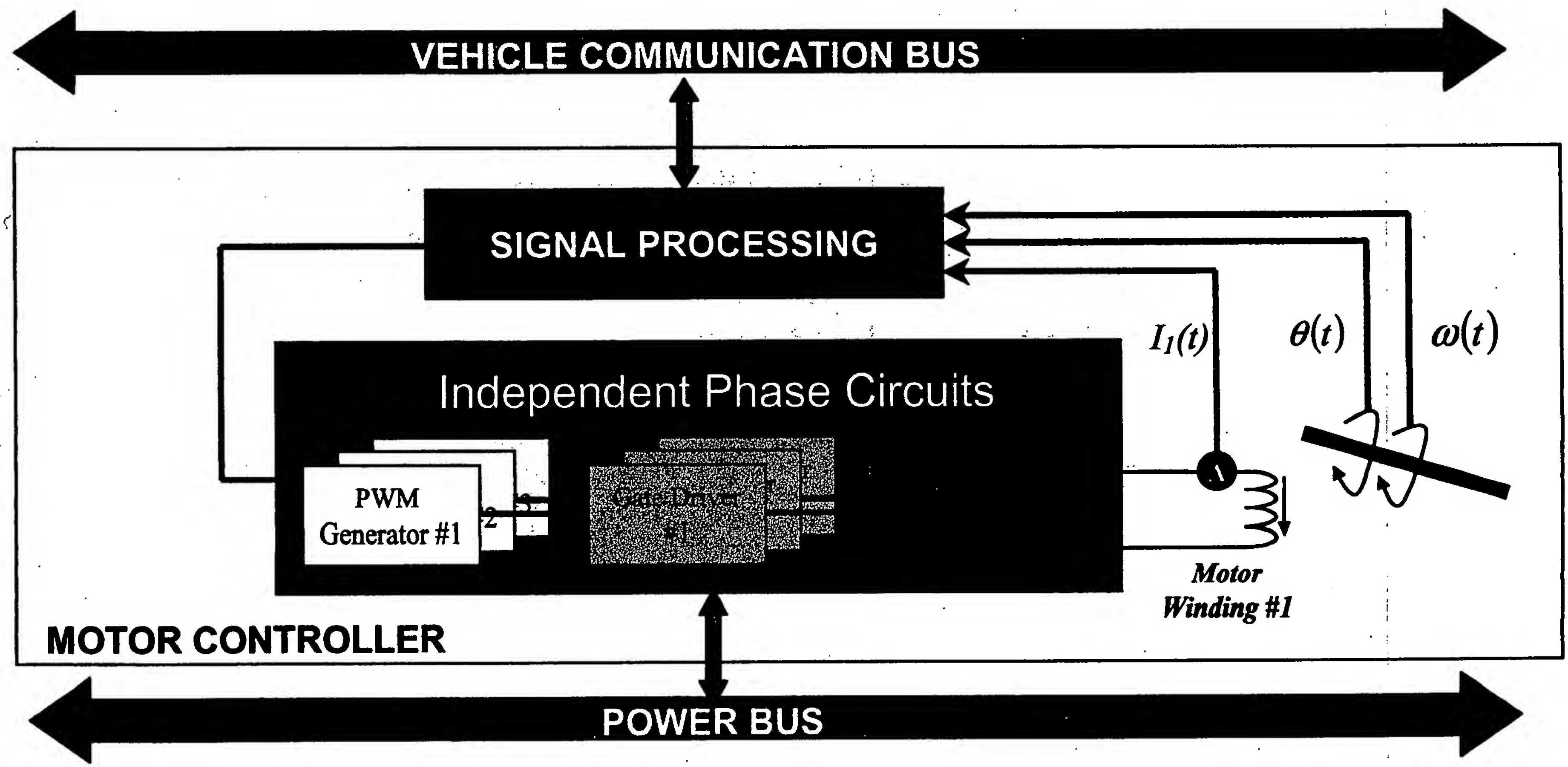

Adaptive Controls Design

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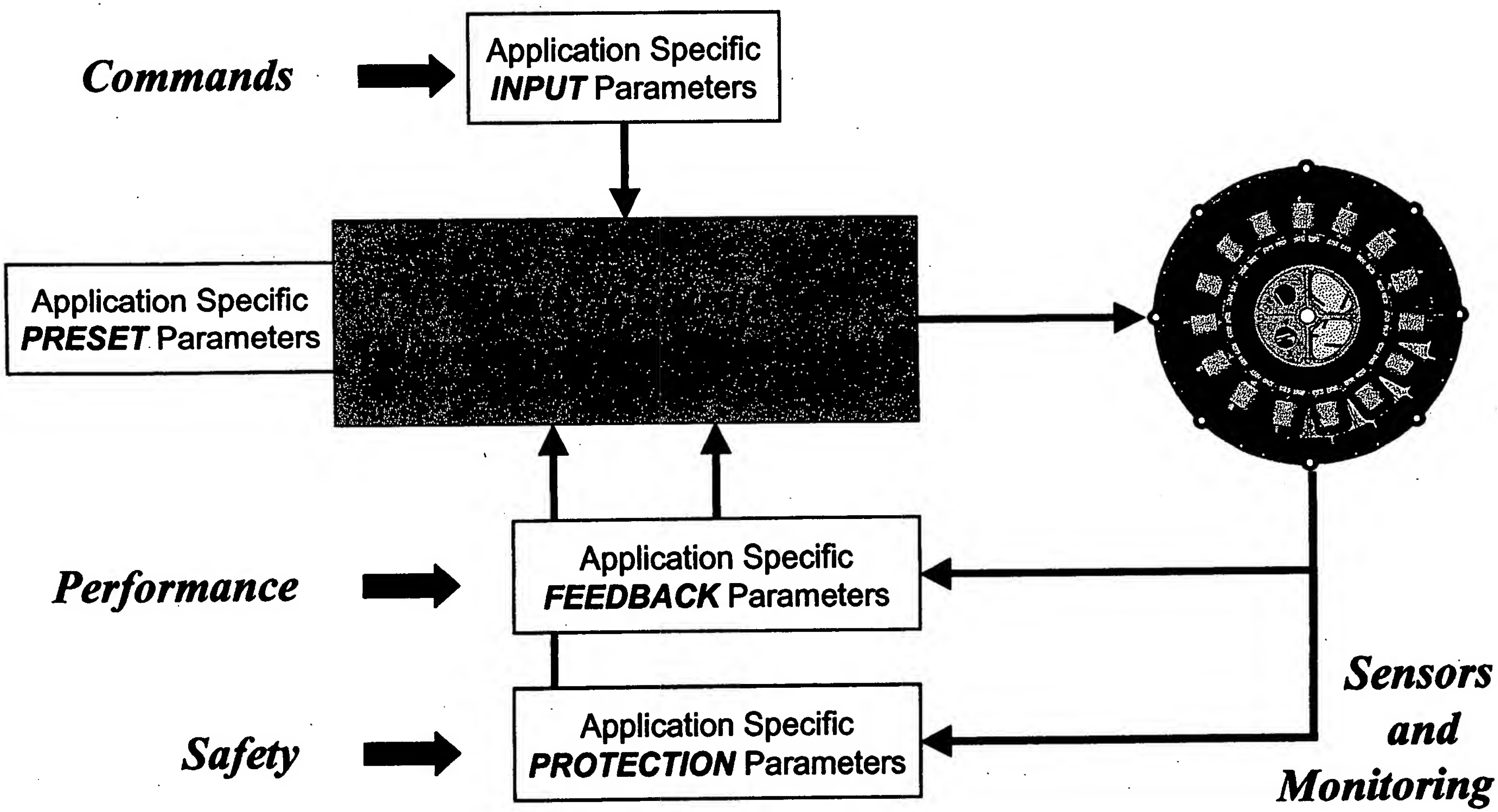
Control System Architecture



Adaptive Controls Design

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Application Specific ***PRESET*** Parameters

- Motor ***PRESET*** Data:
  - Number of phases and magnetic pole pairs
  - Gross weight of the unit
  - Max. Net weight of the unit
  - Min & Max angular velocity
  - Min & Max torque (derived)
  - Min & Max gradient
  - Min & Max current per phase
  - Min & Max supply voltage per phase
  - Min & Max operating temperature
  - Min & Max back EMF / Phase
  - Min & Max duty cycle
  - L and R / phase
  - K_W. K_{EMF} and k_T constants (Angular speed, EMF & torque gain factors)
  - K_{pi} and k_{ii} constants (Partial and integral gain factors)
  - K_{pw} and k_{iw} constants (Partial and integral angular speed gain factors)

Adaptive Controls Design

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Application Specific
INPUT Parameters

↓

- User ***INPUT*** Command Data:
  - Battery status
  - Power / throttle control
  - System temperature
  - System angular velocity
  - System total current consumption
  - System voltage consumption

Adaptive Controls Design

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- System ***PROTECTION*** Safety Data:
  - Current over load shutdown for Phase #1 to #N
  - Short circuit shutdown for Phase #1 to #N
  - Thermal shutdown for Phase #1 to #N
  - System thermal shutdown
  - Low power system shutdown
  - Power supply failure / system shutdown
  - Battery monitoring

Application Specific
PROTECTION Parameters

Adaptive Controls Design

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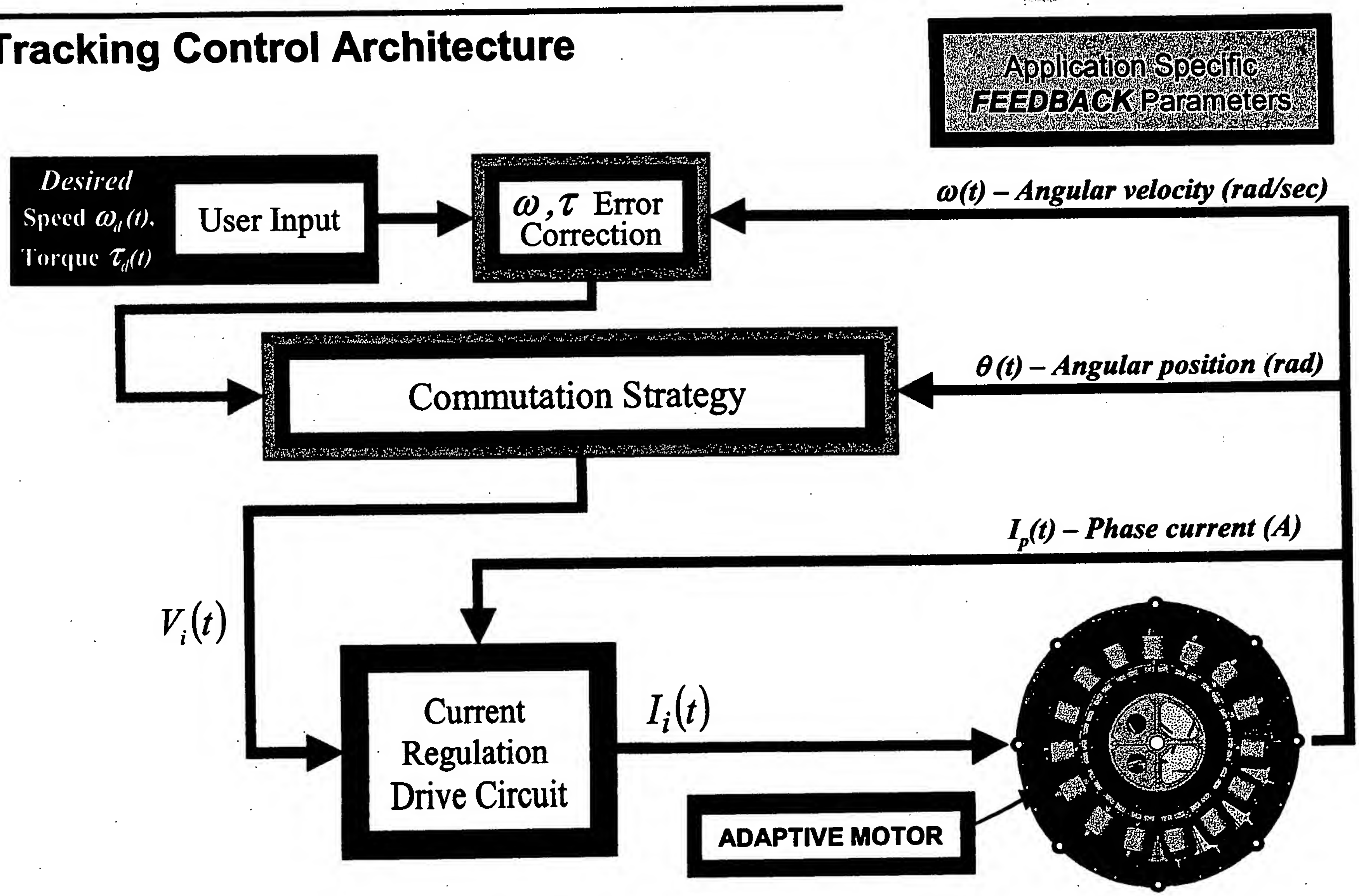
Tracking Control Architecture



INVERTER ARCHITECTURE

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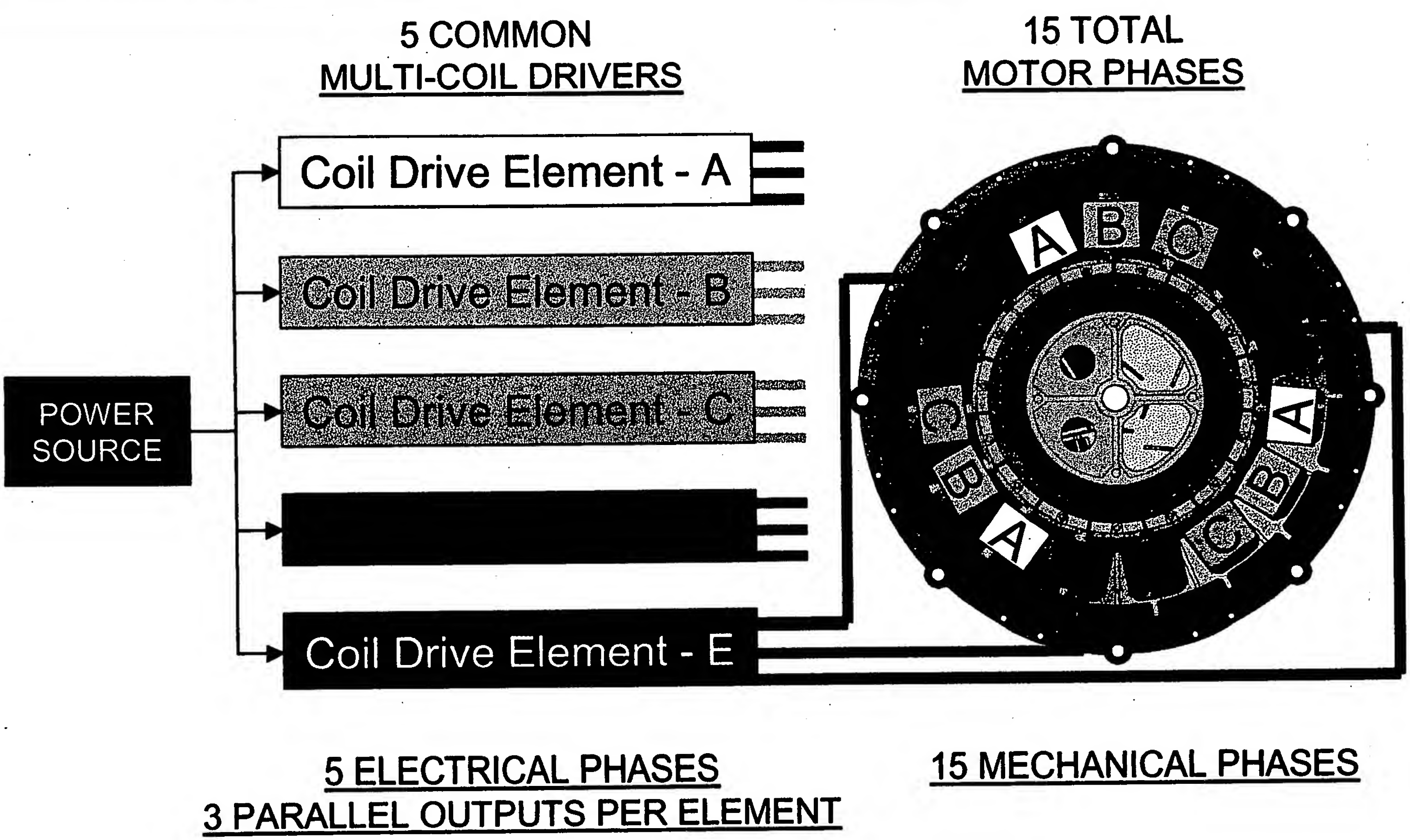

An example of Adaptability

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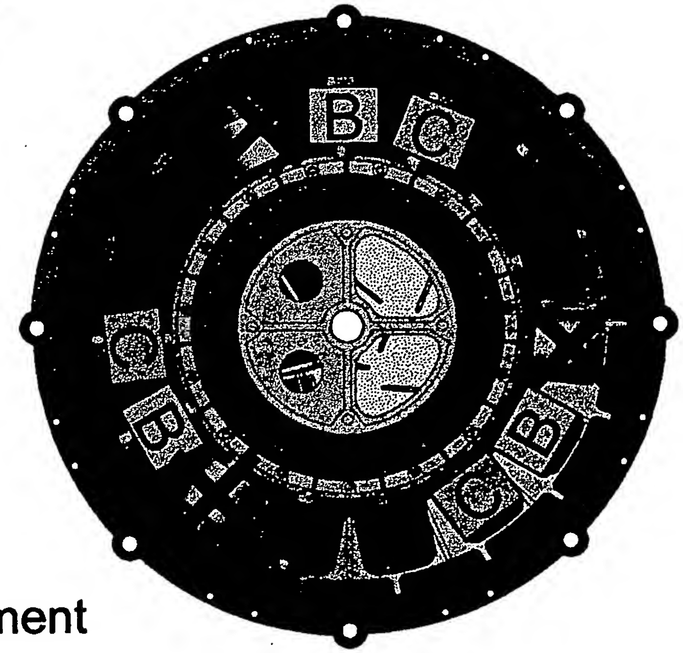

- **<u>A Fault Tolerant System</u>**
  - Consequence of the Loss of a Phase
    - Motor will still operate, but with:
      - Increased torque ripple
      - Increased cogging
      - Decreased torque
  - Adaptive OPTIONS:
    - Bridge the gap in torque
      - Take down the whole Coil Drive Element
      - Redistribute phase torque across remaining CDEs, while maintaining symmetry
    - Manage the imbalance
      - Depending on the number of functioning phases, redistribute phase torque across remaining phases

RESULT: Optimized "GET HOME" capability with minimal effect to the operator

Adaptive Controls Design

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Motor Control Summary

- Control strategy is optimized to balance:
  - **Functional Requirements**
  - **Performance Quality**
  - **System Efficiency**
  - **System Safety**
  - **Fault Tolerance**

- The segmented Electrical and Mechanical Phases allow circuit independence, while balancing configuration, circuitry, power requirements, component complexity, software complexity

- Based on the user inputs and environmental, motor or system conditions, the Control priorities will be adapted to optimize performance

Motor's Performance

Comparing Motor Technologies

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- Applications of Electric Motors in Automotive Industry

FEATURES	Induction	Switched Reluctance	Brushless DC / AC		
			Synchronous	Interior PM	E^{n}Power*
Robustness	+	+			+
Motor Cost	+	+			+
Efficiency			+	+	+
Open-loop Control	+			+	+
Closed-loop Control		+	+		+
Torque Ripple	+	- -		+	+
Wide-speed Range	+	++			++
No Position Sensor		-	-	+	
Acoustic Noise		-			+
Single-point motor failure*	-	+	-	+	+++
Inverter size*	-	-	-	+	+

Reference M. Ehsani, A. Emadi (APEX 2003)

* - Added by Wavecrest Labs

Comparison with Competing Technologies

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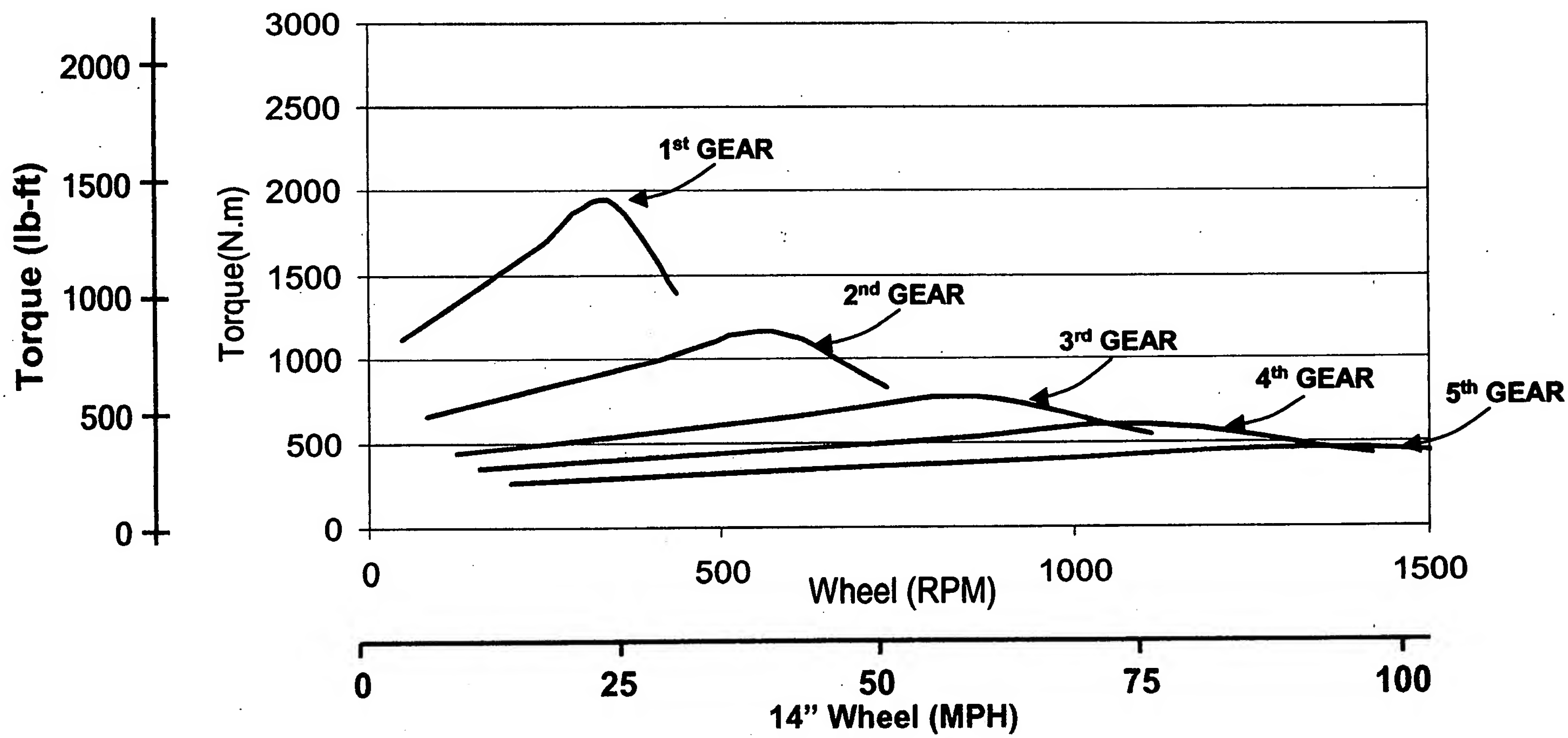
Honda Civic Performance



Comparison with Competing Technologies

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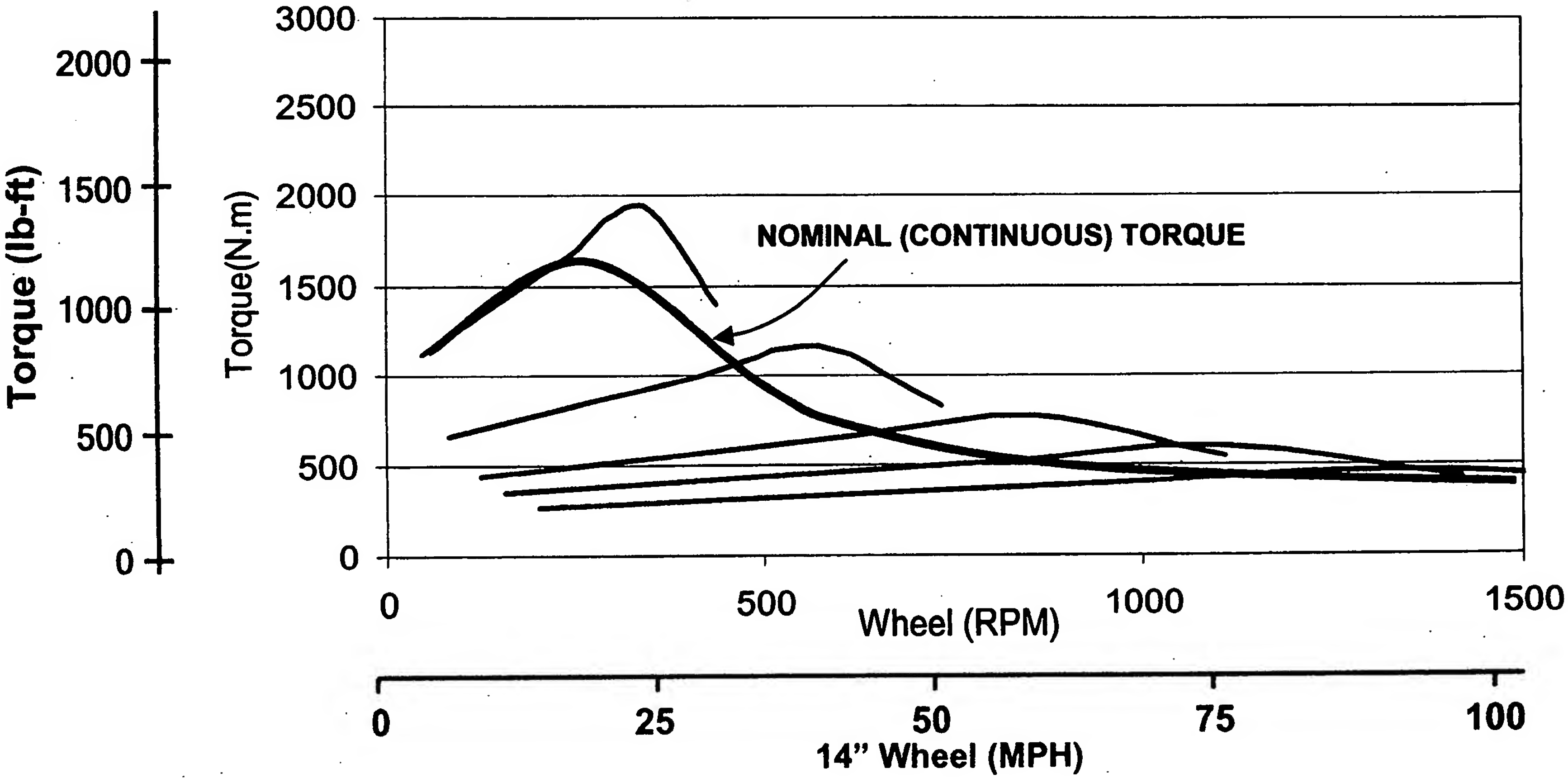
Honda Civic Performance



Comparison with Competing Technologies

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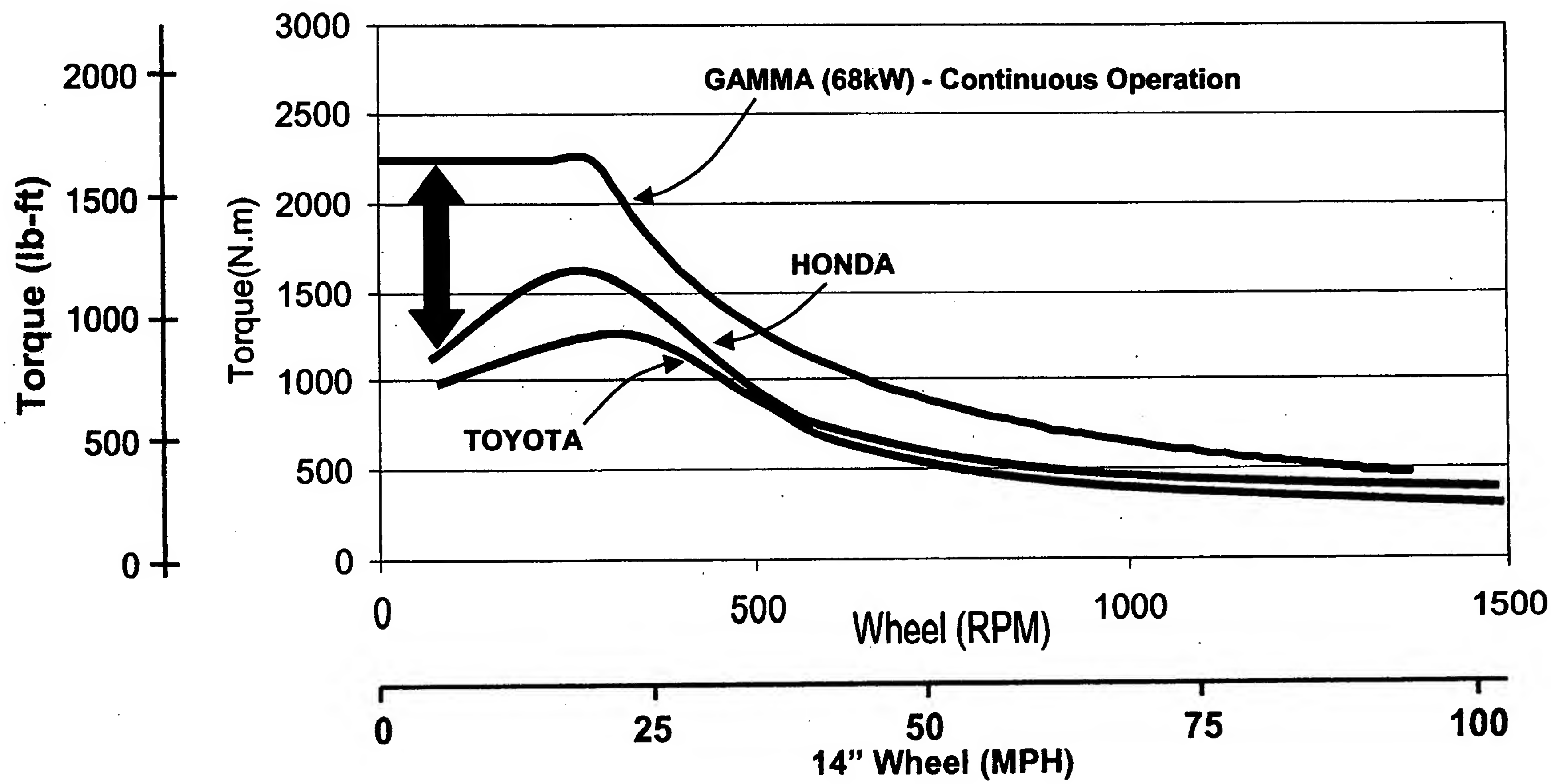
More Than Twice the Low-End Torque



GAMMA Motor Performance

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MOTOR	PEAK POWER	PEAK TORQUE	VOLTAGE LEVEL	ACTIVE MASS	TORQUE DENSITY
	HP (KW)	lb-ft (Nm)	Volts	lbs (kg)	lb-ft/lb (Nm/kg)
Enova Systems EDM - 60	80 (60)	117 (159)	220	123 (56)	.95 (2.8)
Unique Mobility *PowerPhase 100*	135 (100)	405 (550)	300	190 (86)	2.1 (6.4)
Unique Mobility *SR218N*	71 (53)	177 (240)	300	105 (48)	1.7 (5.0)
Voith *ELVO drive*	202.5 (150)	2028 (2750)	220	486 (220)	4.2 (12.5)
WaveCrest *E^nPower (4)*	91 (68)	1918 (2600)	42	265 (120)	7.2 (21.7)

E^nPower Propulsion System

Automotive Leadership Team

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- Rick Eagle
  - 15+ years of automotive and entrepreneurial experience, MBA
  - Urban Data Solutions - Vice President, Product Development
  - Ford Motor Company - Product Manager, Escape HEV
- Kevin Pavlov
  - 15+ years of automotive experience, MBA, MS
  - Visteon - Manager, Advanced Chassis and Dynamic Systems
  - Ford Motor Company - Manager, Chassis Systems
- David Smith
  - 20+ years of automotive and entrepreneurial experience, MBA
  - Energy Consultants - President and Founder
  - Exide Battery - Vice President, Emerging Technology
  - DaimlerChrysler - Manager, Advanced Technology
- Joanne Woestman
  - 15+ years of automotive experience, MBA, PHD
  - Ford Motor Company – Manager of Hybrid Systems Engineering
- Gary Gloceri
  - 15+ years of automotive experience, MBA
  - Visteon – Manager, Vehicle Controls, Suspension Systems
  - Allied Signal – Bendix – ABS System Development

WaveCrest's Hybrid System

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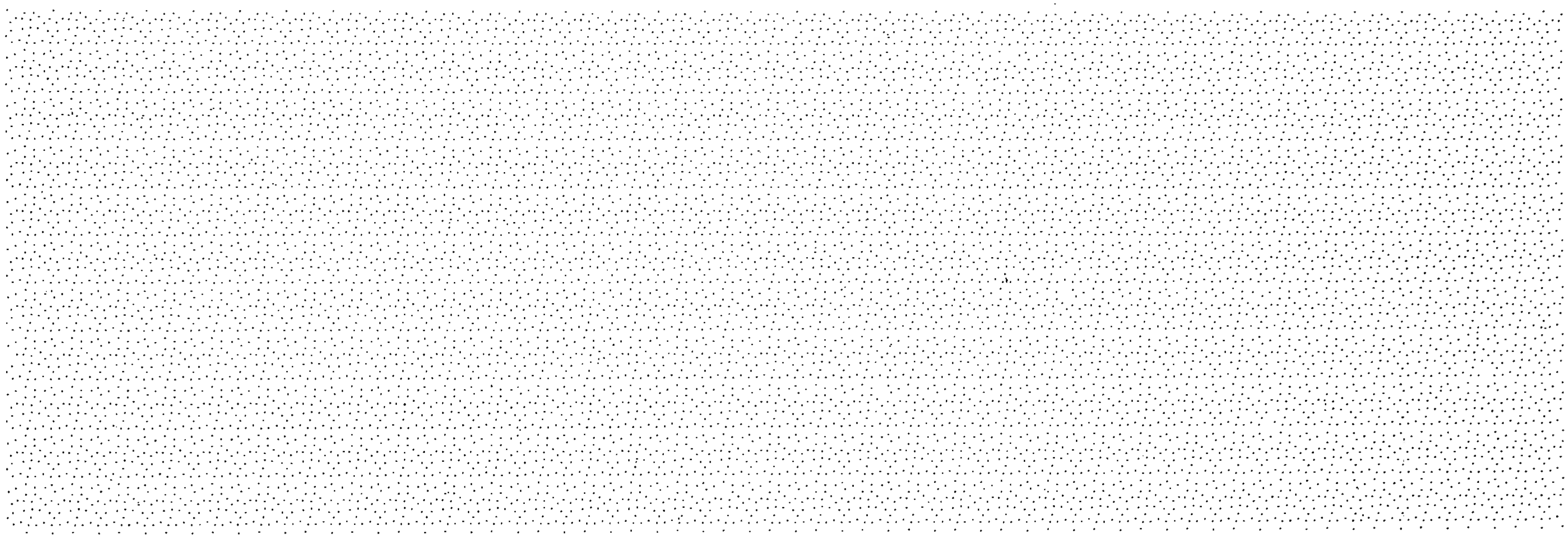

Systems Engineering Solution

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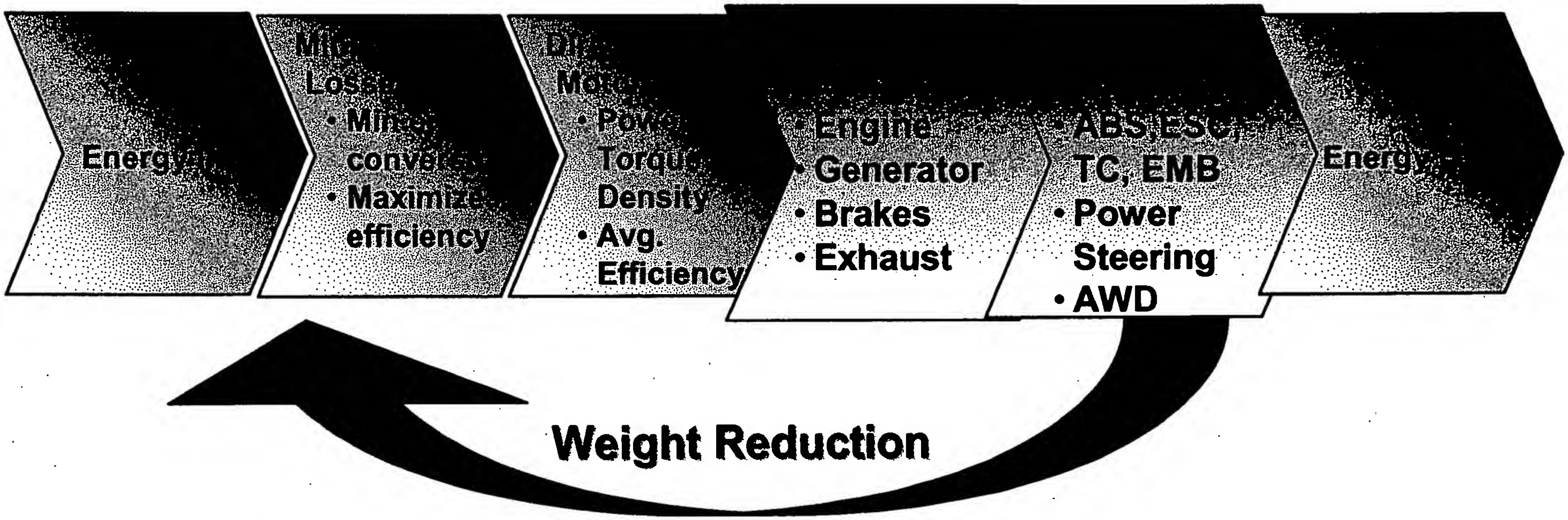
Total Energy Management Solution



WaveCrest Enablers

- Distributed currents ➡ lower system voltage ➡ lower cost, losses
- High average efficiency ➡ greater downsizing
- Fast response and high torque at low/zero speed ➡ dynamic functions

Low Voltage Solutions

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- Distributed architecture enables lower system voltage requirements
- The cascade effect follows:
  - Enhanced safety (redundancy and lower voltage)
  - Lower cost power electronics
  - Industry standard connectors, conductors, and circuit protection
  - Opens path to lower cost battery technologies, simplified battery management and wider packaging options

Wavecrest E^{n}Power Battery Comparison

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Power Battery Capacity

E^{n}Power Motor & Battery System	60 kW
E^{n}Power Motor System	32 kW
Today – BIC HEV	20 kW

Wavecrest low voltage motor systems enable the power battery to deliver higher performance

- Fewer cells in series provides better cell balance, more robust performance
- Simple thermal management & voltage control reduces peripheral cost, weight and energy losses
- Lower cost chemistries possible (PbA vs. NiMH or LiIon) at higher safety factors

Wavecrest E^{n}Power
Advanced Battery Comparison

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Comparison of conventional battery construction to
Wavecrest PowerPackage

- Example is for a Gamma motor 17kW, 12 second acceleration (57Whrs)

Conventional | **Wavecrest PowerPackage**

Chemistry	P:E	E_{Whr}	Whr/kg	kg/lbs	Wavecrest PowerPackage	$$
PbA	16:1	1060	30	35/77	[redacted]	25
NiMH	12:1	1400	45	31/68	[redacted]	100
LiIon	18:1	950	75	13/29	[redacted]	200

E^nPower Battery Performance Goals

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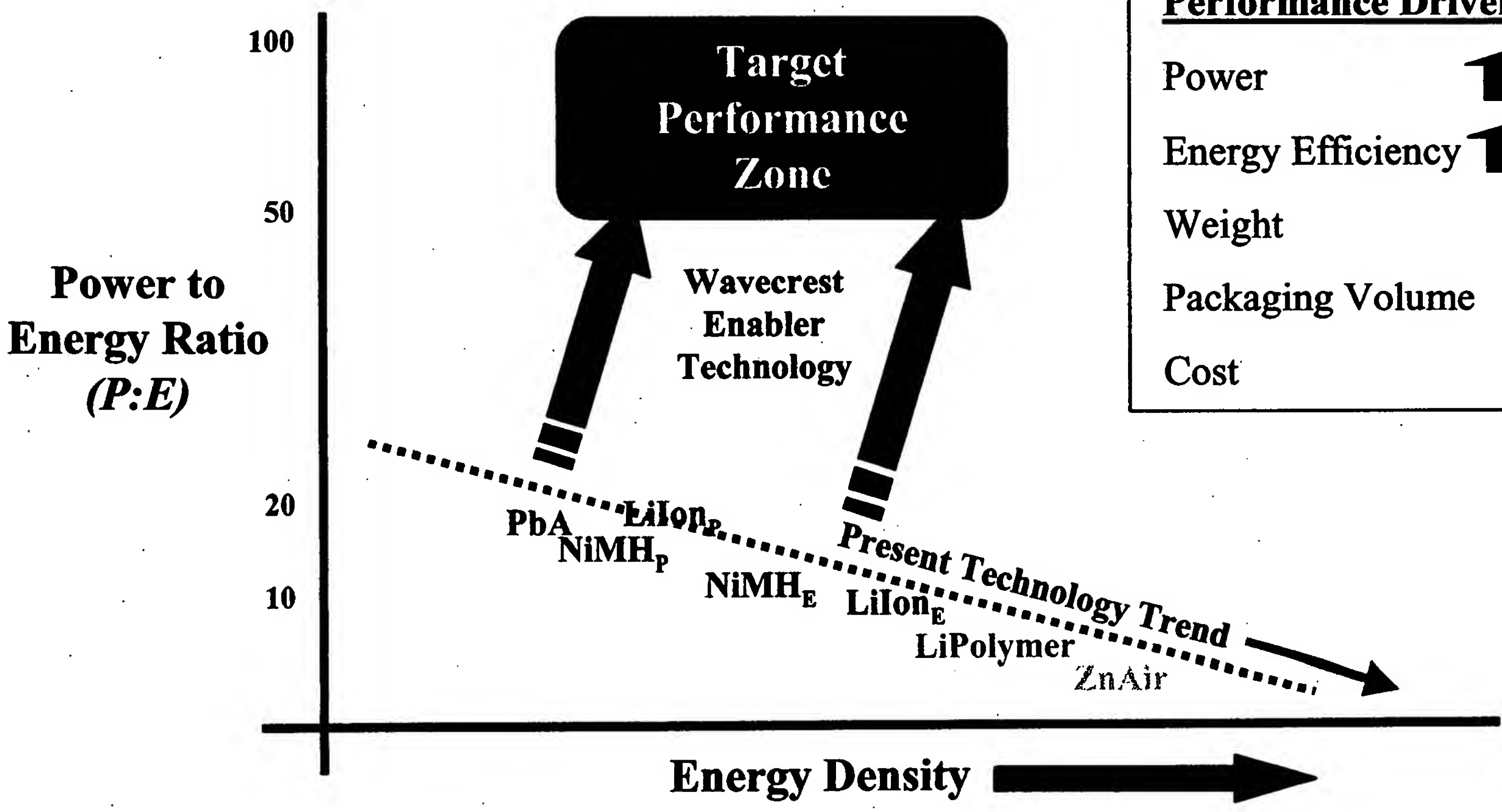
Wavecrest PowerPackage unique battery <u>design</u> allows increased power



Performance Drivers:

- Power ↑
- Energy Efficiency ↑
- Weight ↓
- Packaging Volume ↓
- Cost ↓

E^{n}Power Battery Solutions

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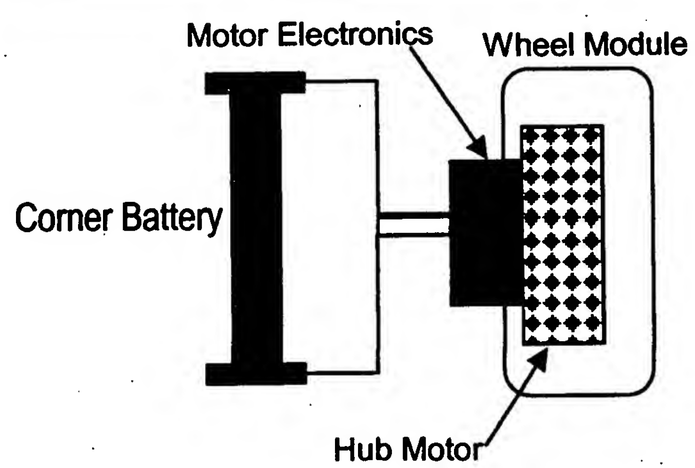
HEV Battery Cost

Today – BIC HEV (LiIon)	$1500-$2000
E^{n}Power System (NiMH)	$1000-$1200
E^{n}Power System & Battery Design (PbA)	$250-$500



E^{n}Power provides opportunity to change the battery system:

- Increase power density, lower stored energy required
- Potential independent wheel storage paradigm
- Unique designs in power batteries
  - Improved mechanical package of current chemistries to achieve premium performance from any chemistry
  - High power to weight ratio, very low impedance irrespective of chemistry
  - Common pressure vessel design, low part count
  - Reduced failure modes, excellent durability, superior $$/watt performance

Stacked Cell Battery Design

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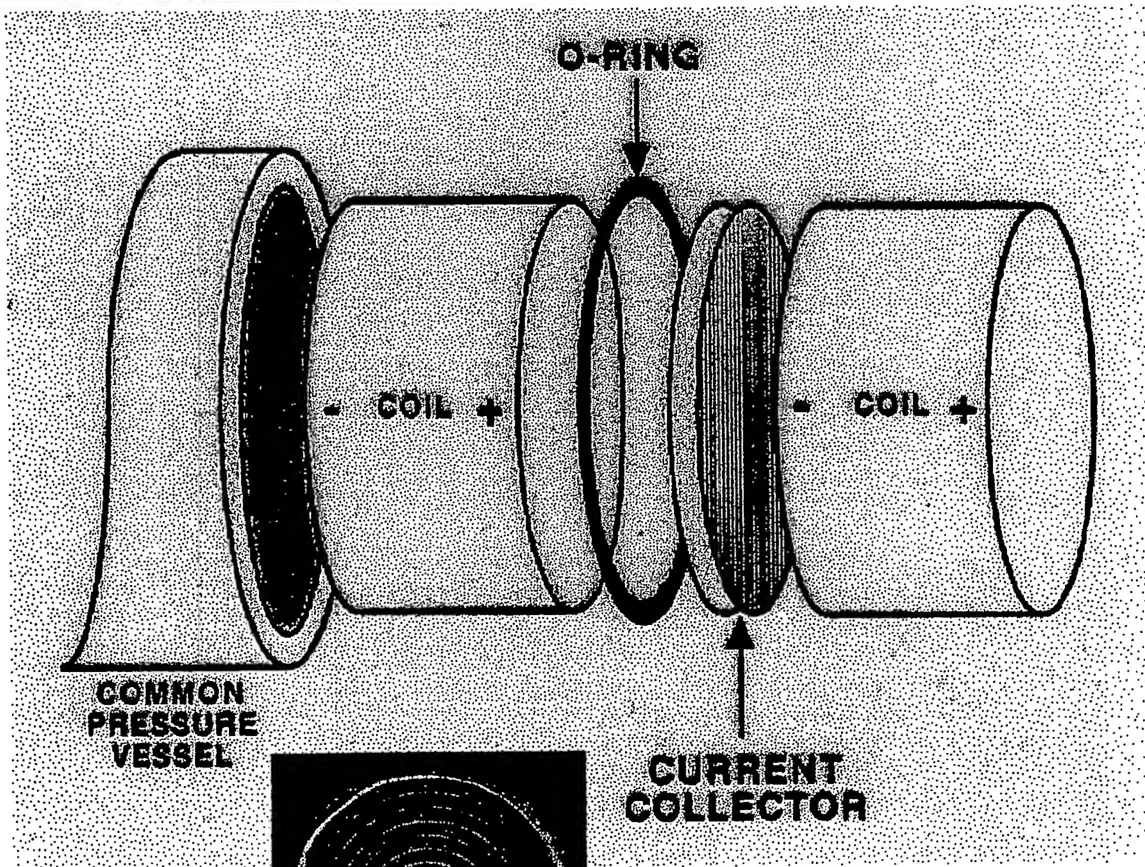
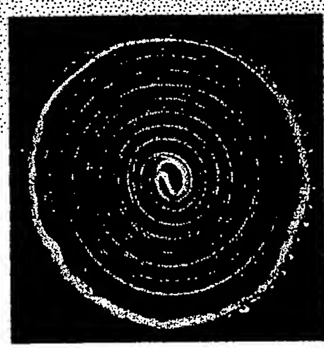
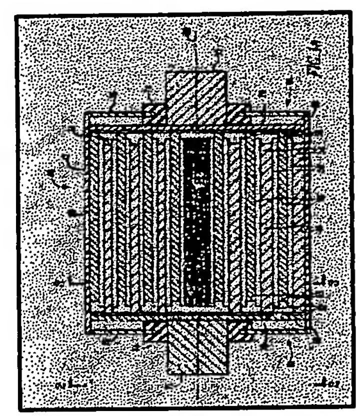




- ➢ High surface area current collectors
- ➢ Common pressure vessel design
- ➢ O-Ring sealing for pressure equalization, thermal expansion
- ➢ Low part count, lower cost
- ➢ Chemistry independent



Patented Cell Design

Power Battery Design Direction

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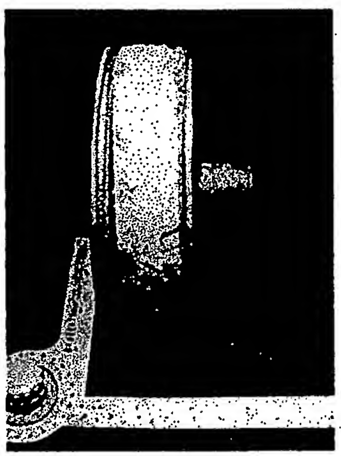
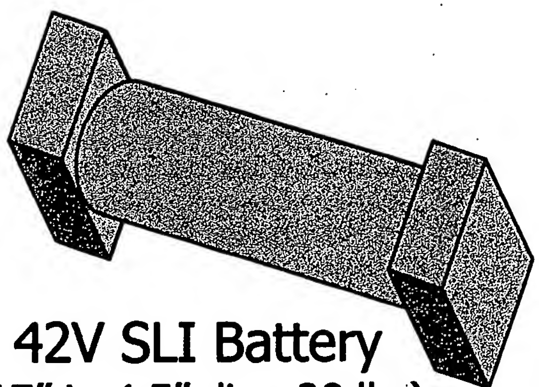
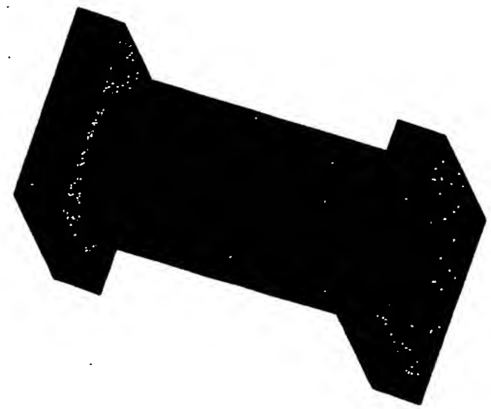
Conceptual Battery Designs in Lead Acid Technology

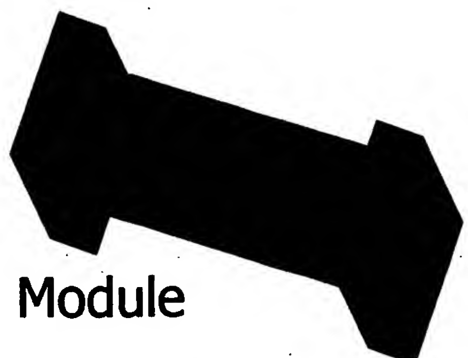




42V SLI Battery
(17″ L, 4.5″ dia., 28 lbs)



48V HEV Power Module
(10Ahr, 13.5″ L, 5.3″ dia., 32 lbs)
50kW power capacity



48V HEV Power Module
(5Ahr, 13.5″ L, 3.8″ dia., 16 lbs)
25 kW power capacity

Comparable NiMH batteries would be 1/3 smaller and 2.3 X lighter

Comparison of Battery Discharge Performance

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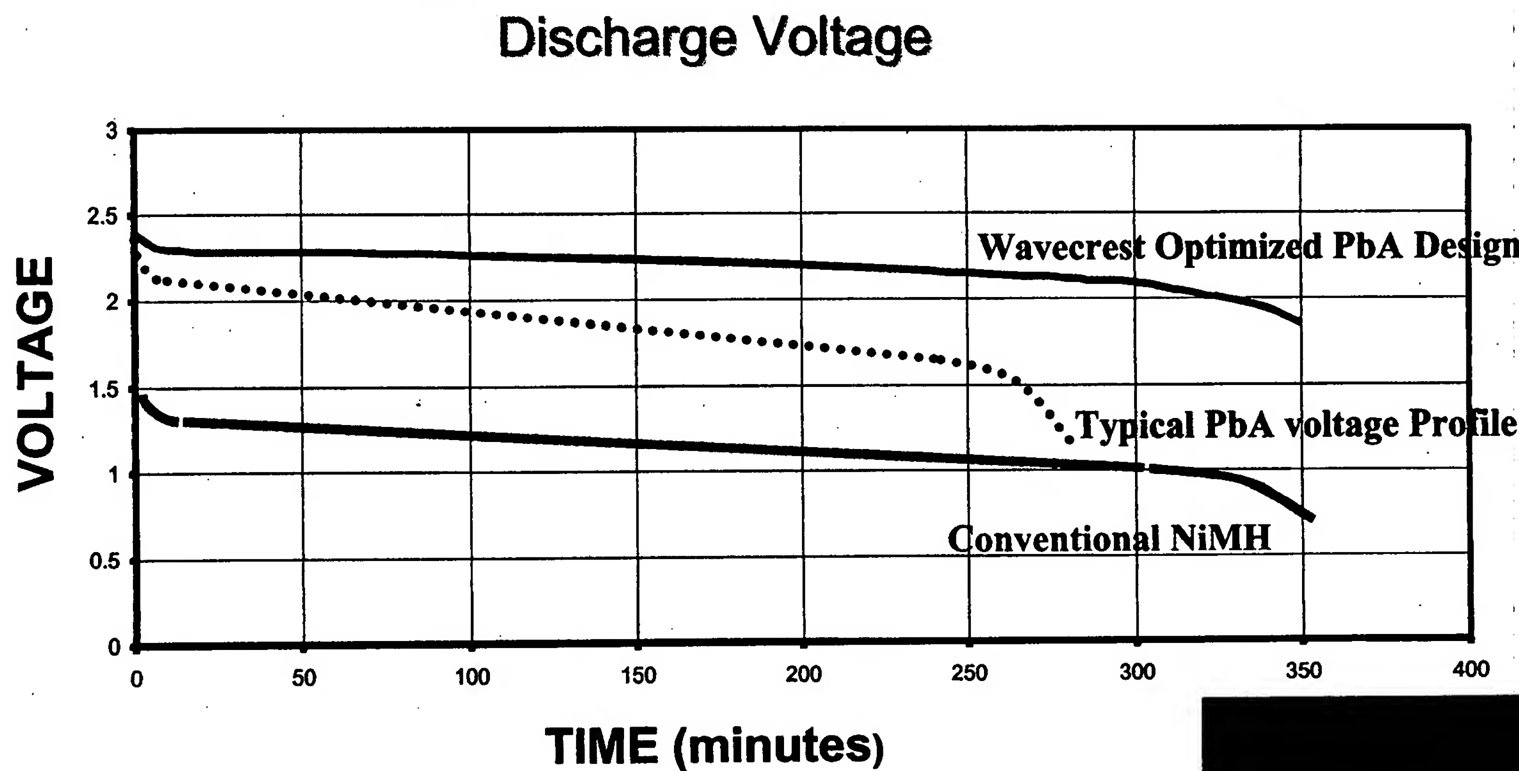

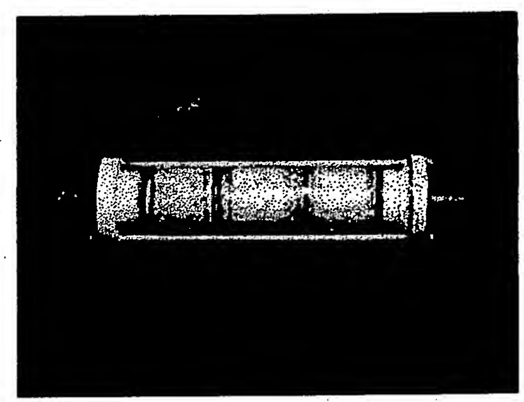

PbA Developmental Cell for Optimized Design

HEV Power Usage – Ideal
(100kW Automotive Drivetrain)

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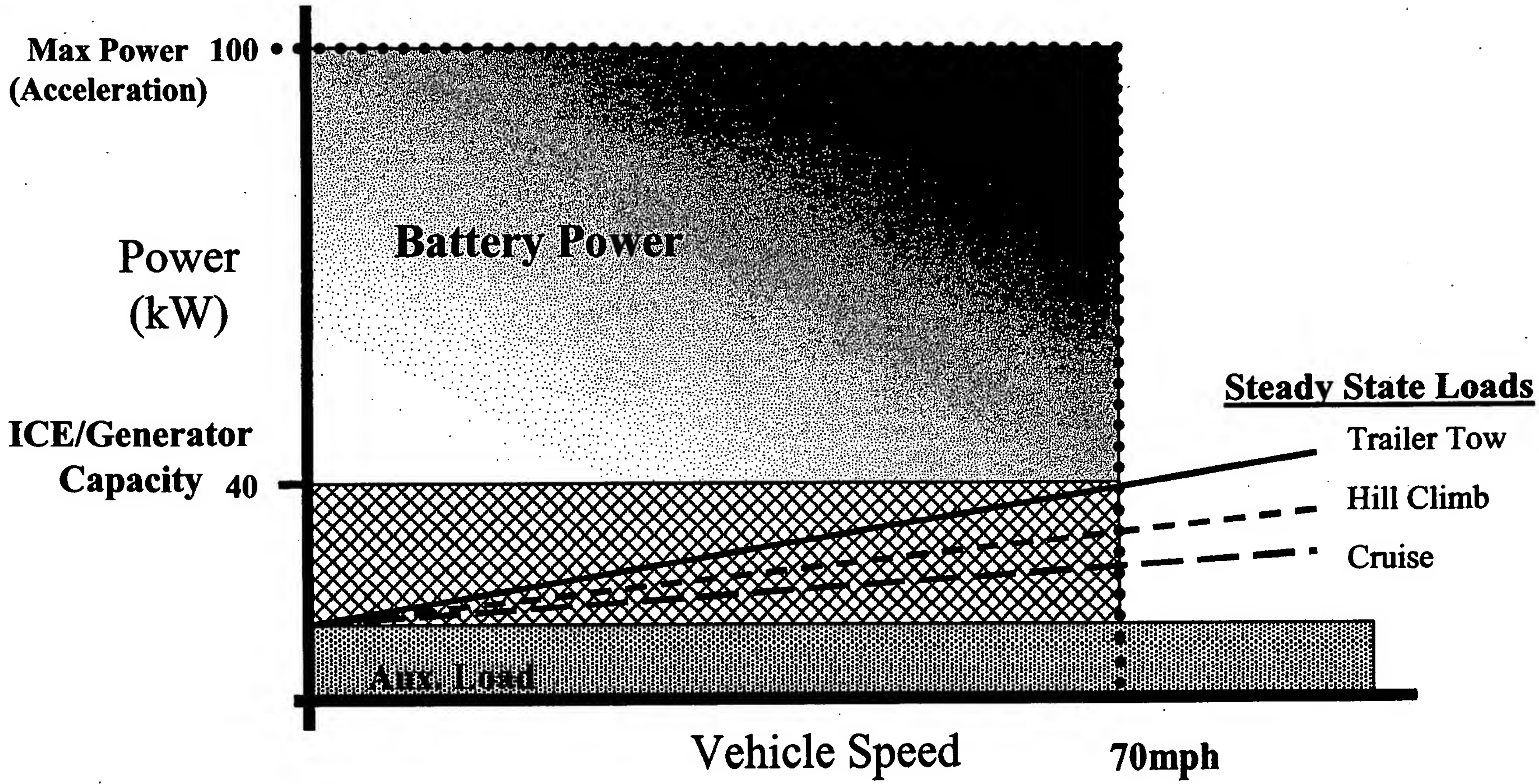

Battery (60kW) + ICE/Generator (40kW) = 100kW demand

HEV Power Usage
(conventional, high voltage system)

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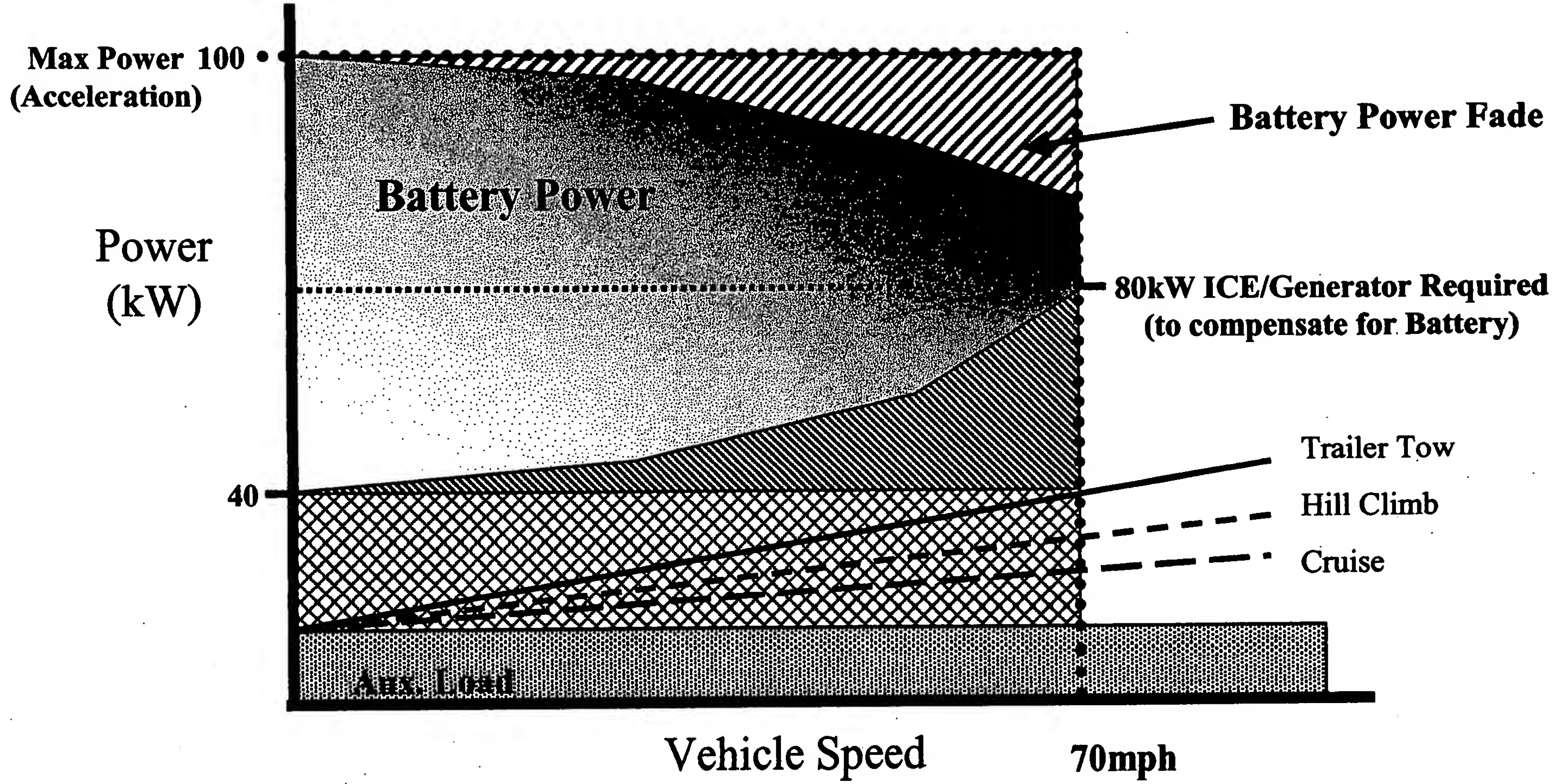

Battery (20kW) + ICE/Generator (80kW) = 100kW demand

Wavecrest E^{n}Power
Internal Combustion Engine Down Sizing

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HEV ICE/Generator Capacity Requirement

100% — Today – BIC HEV

85% — E^{n}Power Motor System

50% — E^{n}Power Motor & Battery System

*Less than 20% of the total engine power produced in a conventional mechanical driveline reaches the wheels

Increasing system efficiency, Wavecrest can approach ideal Hybrid model*

- Low system voltage reduces battery fade and losses in power electronics
- Motor's high average efficiency minimizes power requirements throughout drive cycle
- Direct drive motors minimize mechanical losses
- Weight Optimized
    - Light weight drive motors
    - No driveline components
    - Battery size minimized
    - System Consolidation
    - Foundation Brakes
    - Engine

System Consolidation
Vehicle Dynamics

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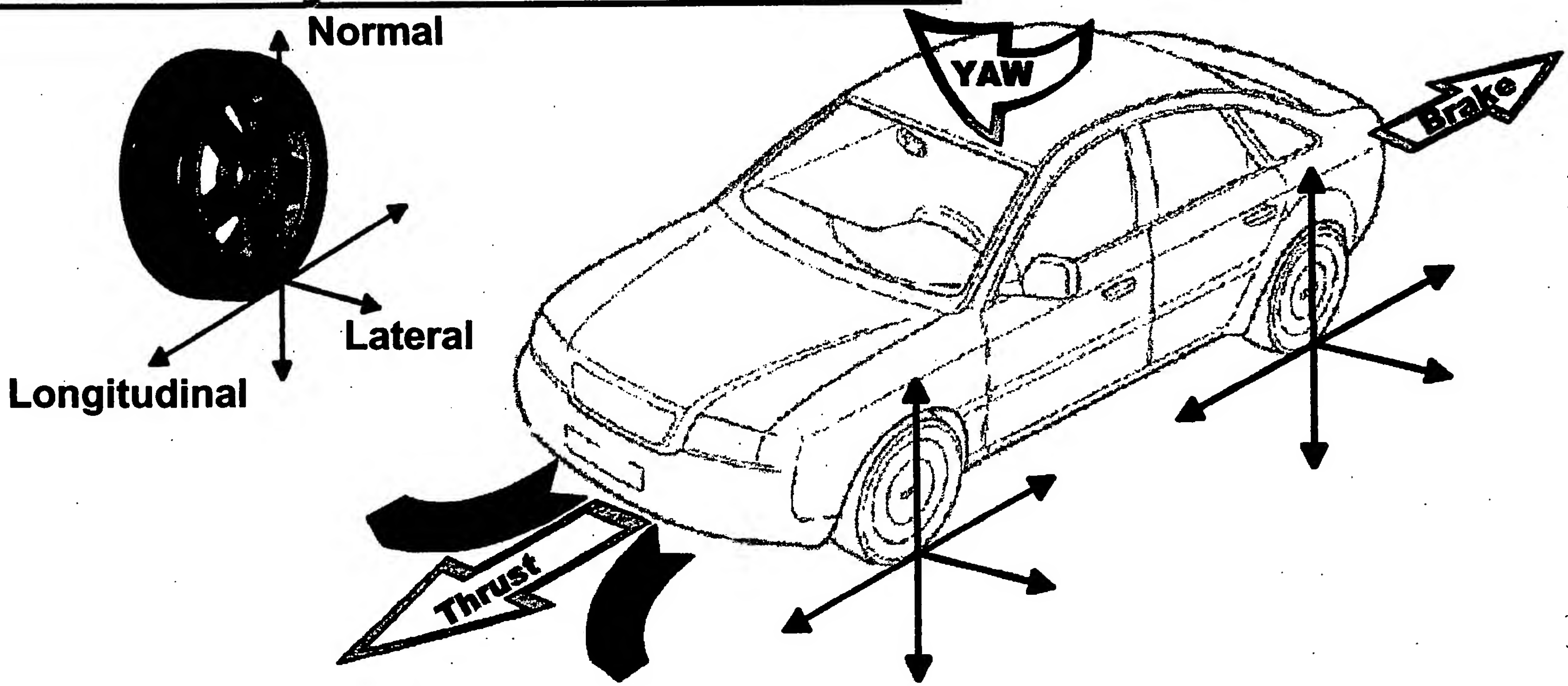

Motor can perform other system functions

- Zero speed torque (Integrated brake system features)
- High frequency response enables Yaw torque production which creates positive effects on steering, stability, and braking

System Consolidation
Vehicle Dynamics

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The Wavecrest motor's enabling effect on other vehicle systems:

- ***Zero speed torque production improves*** performance of:

  Anti-lock brakes, Traction Control, Yaw torque / stability management, Brake lining life, Regeneration efficiency, Steering system efficiency, Wheel Speed information…

- ***Motor fast frequency response / low inertia improves:***

  All the above plus: Thrust performance, Stopping distance, torque steer / split torque braking, electrical power consumption

- ***Low RPM / Independent Pole control improves:***

  NVH operation, audible noise, load spikes, failsafe operation

Systems Engineering Solution

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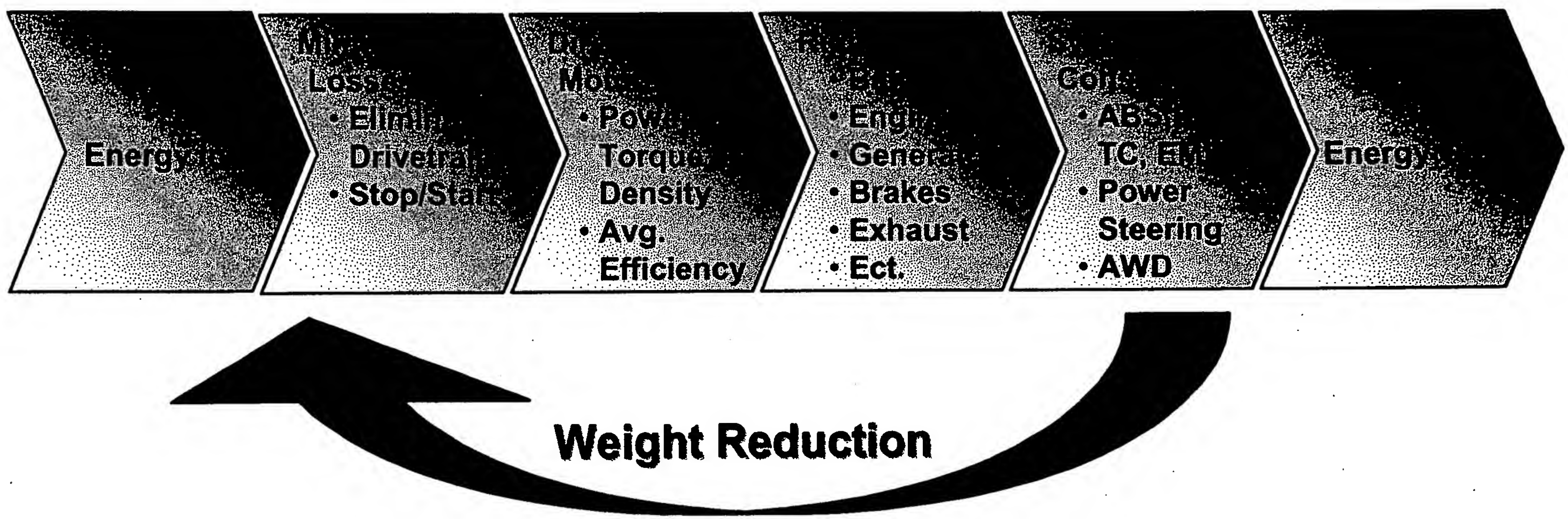
Total Energy Management Solution



E^nPower Applications

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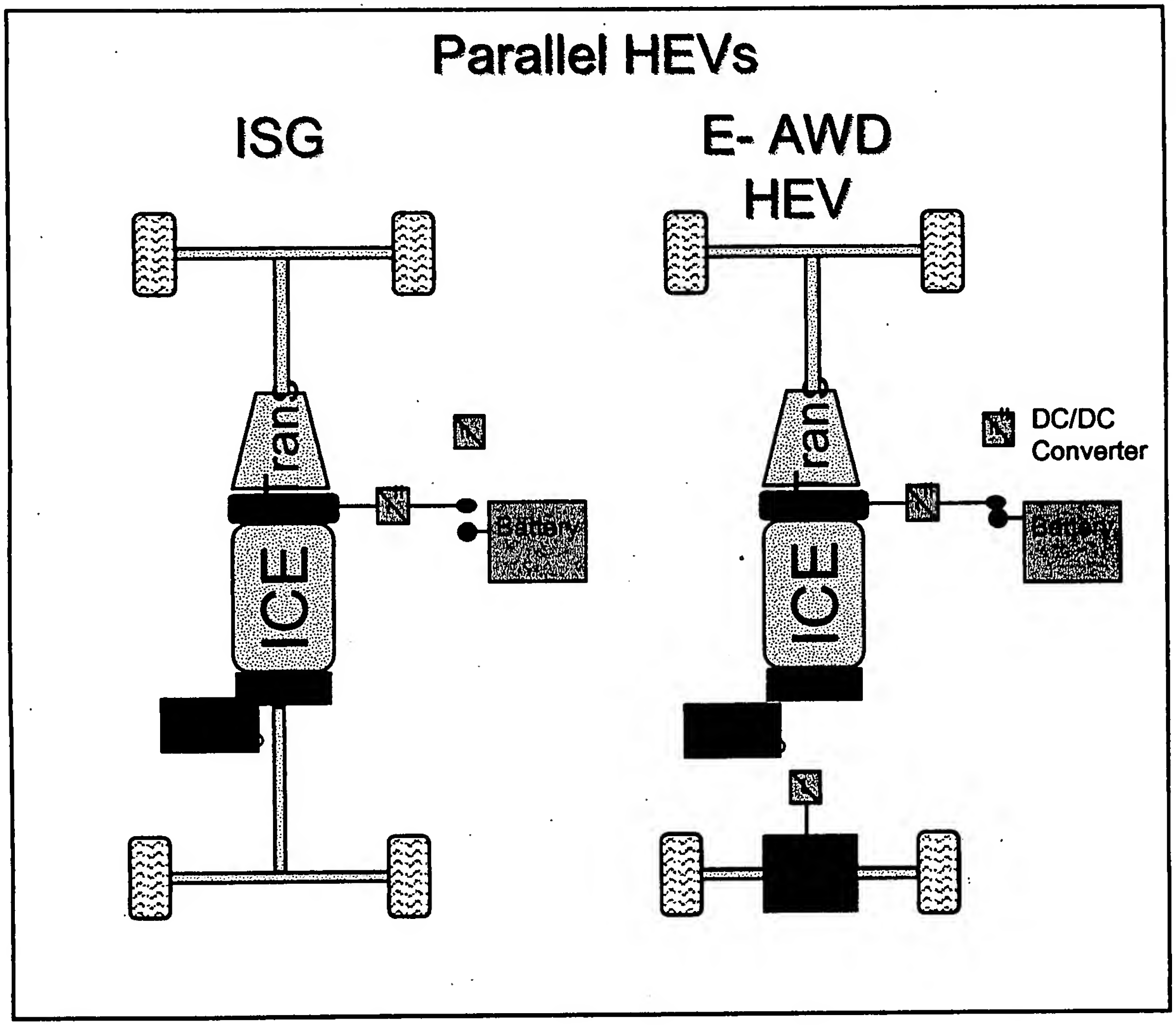

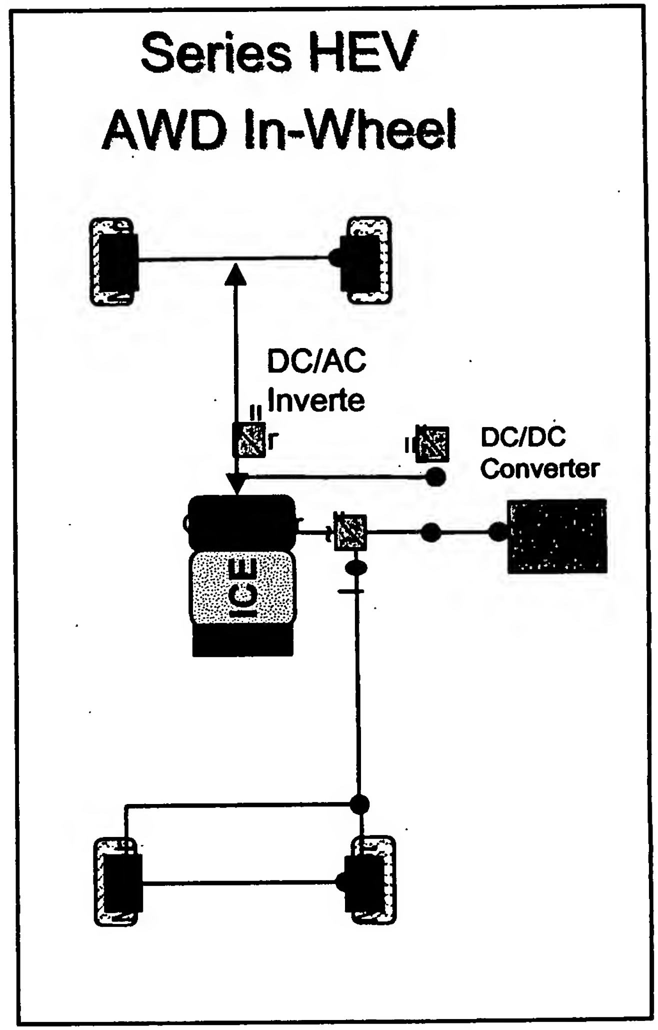

Fuel Economy Walk

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Sensitivity Parameter	Series	Parallel
Motor		
Average Motor Efficieny	0.91	0.05
Motor/Inverter Specific Power	0.03	0.02
Battery		
Ave. Battery Turnaround Eff.	0.15	0.13
Battery Pack Specific Power	0.04	0.02
System/Vehicle		
Ave. Engine Efficiency	1	1
Regen Braking Fraction	0.1	0.07
Vehicle Mass	-0.6	-0.63

- Published NREL *Advisor* results for mid-sized sedans with DI diesels and realistic performance requirements
- Sensitivity = % fuel economy change on combined federal cycle for a 1% change in the parameter

Surpassing Parallel

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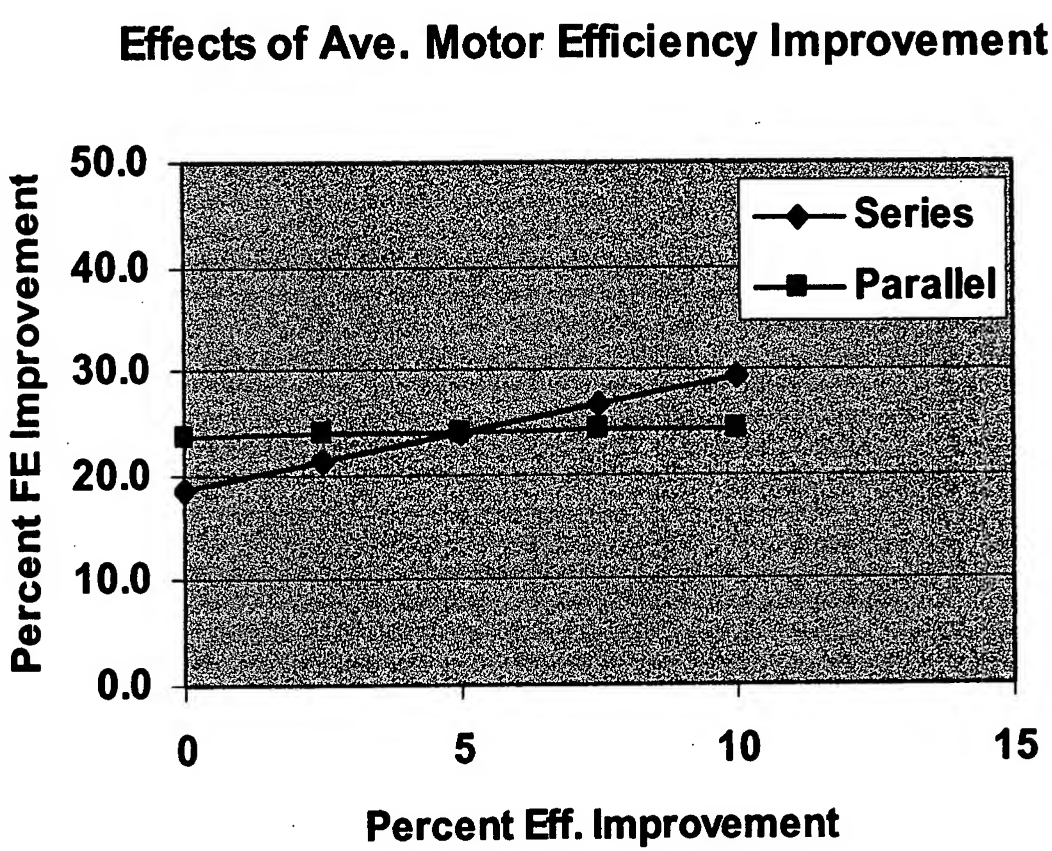

Additional System Impacts

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Components Eliminated	*Components Right Sized*	*Components Added*
Transmission	Engine	Traction Battery
Axles	Emission System	Wheel Motors
Drive shaft	Cooling System	Generator
Transfer case (4x4)	NHV/Heat Insulation	VSC–Power Electronics
Starter/Alternator	Fuel System	Electrical Distribution
Master cylinder	Brake Rotors	DC-DC converter
ABS/TC/ESC		
12v starter battery		

Automotive Integration Roadmap

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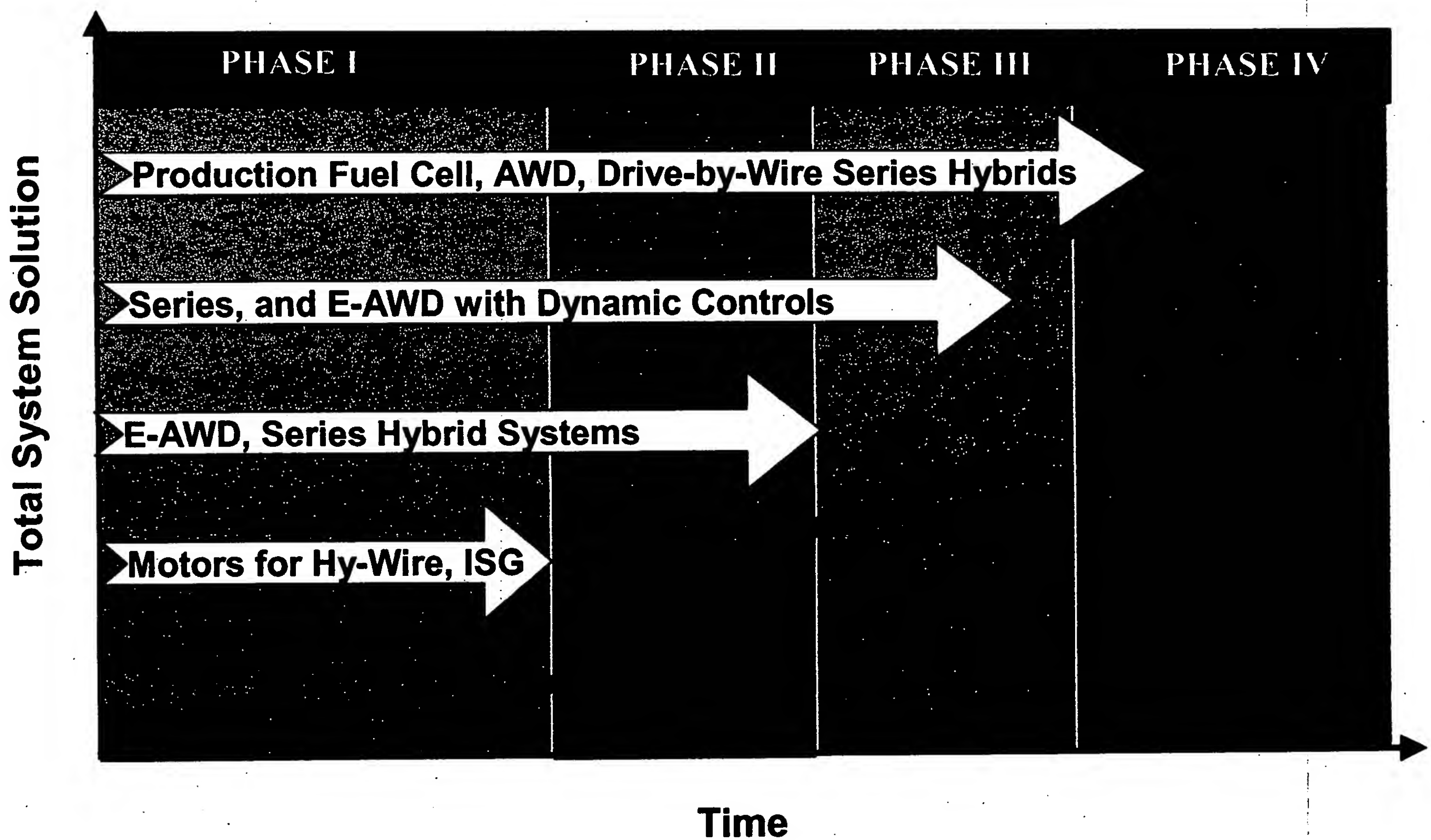

Next Steps – Wavecrest's Requests

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- Disclosure and regular briefings of GM and Wavecrest plans
- Collaboration on identifying how Wavecrest can accelerate the plans and improve the products
- Development funding and demonstration vehicles
  - ISG or EAWD for near term development
  - Full series system solution for longer term
- Discussions on future business options and an ongoing relationship with GM

GM Electric Drive Product Plans

GM Hybrid Products

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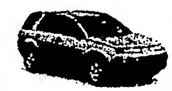
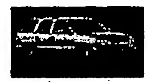
	BAS	FlexPower	FlexPower Electric Assist	ParadiGM +
Initial Product	2006	 2003	 2006	 2005
Other Applications			 2007	Other Frt wl drive Apps.
System Description	Belt Driven Alternator/Starter w/DOD, Vti	Transmission ISG	"Like Civic" Version of Flex Power	Dual Electric Motor System; e-Reverse
Motors		Continental ISAD, between eng/trans	ISAD, between eng/trans	2 – 20 kW motors, ASM
IC Engine	Available on both 4 & 6 cyl	5.3L V8 DOD adds 8% FE DSL by '07	Available on both 4 & 6 cyl	2.0L I4, 125 hp
Battery	36v	42v Panasonic PbA	42v Panasonic PbA	300v NiMH
% Fuel Economy	12-15	10-12	15	50% Nearly 40mpg
System cost /revenue		?/$1000	$2000	$5000 / 3000

GM HEV Product Plan

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- GM will launch an ISG in Full Size Pickup late '03
  - 10-12% FE, primarily due to stop start
  - Mated with 5.3 –liter V8
  - Portable generator for contractors, outdoorsmen (4.8 kw)
  - Mild regeneration capability, small 42v battery
  - Electric hydraulic steering and water pump
  - Military contract for 30k units

GM HEV Product Plan

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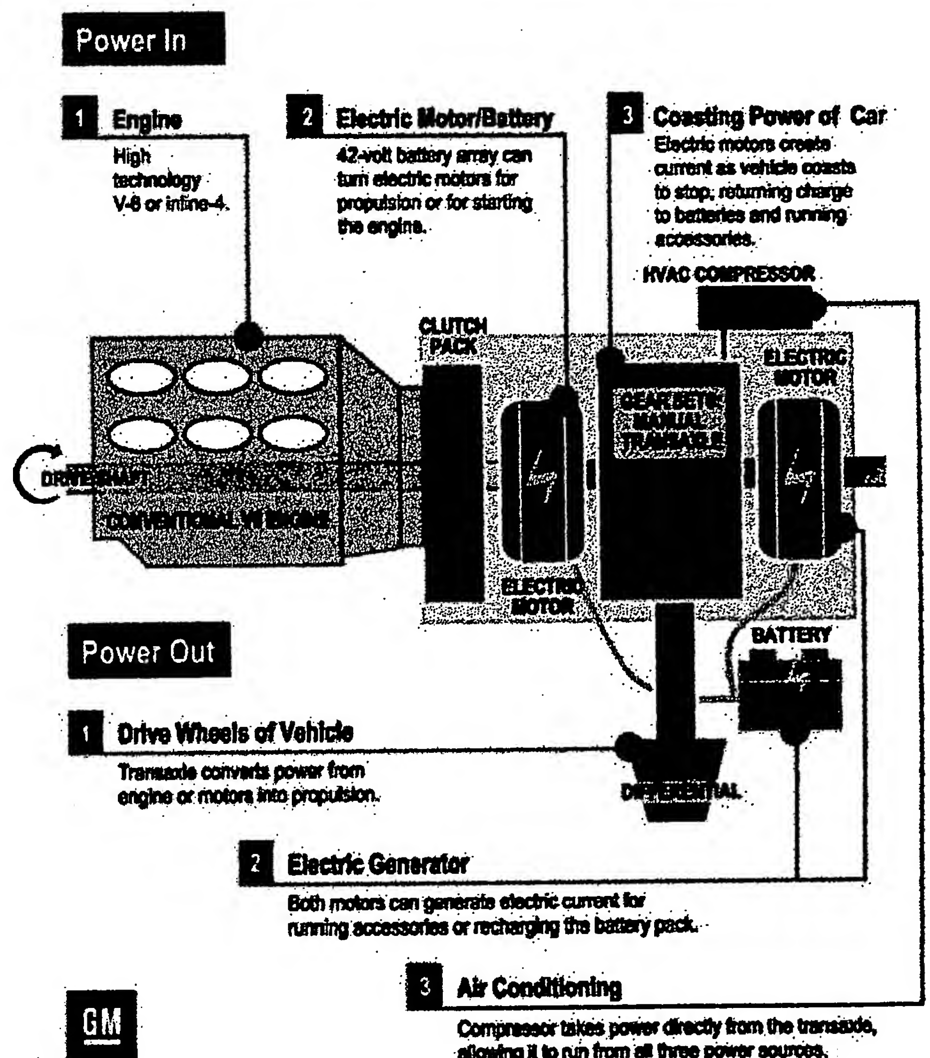
- ParadiGM System launch planned for 2004 in all new SUV
  - New Global platform call the Epsilon, Malibu
  - ParadiGM is a two motor, pre / post transmission architecture mated with an ASM and 3.6-liter V6, 42 and 12 v electrical system
  - 220 HP from V6 and 32 hp from electric motors

GM's ParadiGM System

- 20 % better FE
- 42v, 32kw total
- Electric Launch
- Lead Acid Batteries
- ASM

General Motors' ParadiGM hybrid system

The heart of the new ParadiGM hybrid system being produced by General Motors is a unique transaxle which links a full-sized internal combustion engine with electric motors, the air conditioner compressor and the differential. The system provides 20 percent better fuel economy without sacrificing horsepower or accessories.



The Future for Hybrid Drivelines

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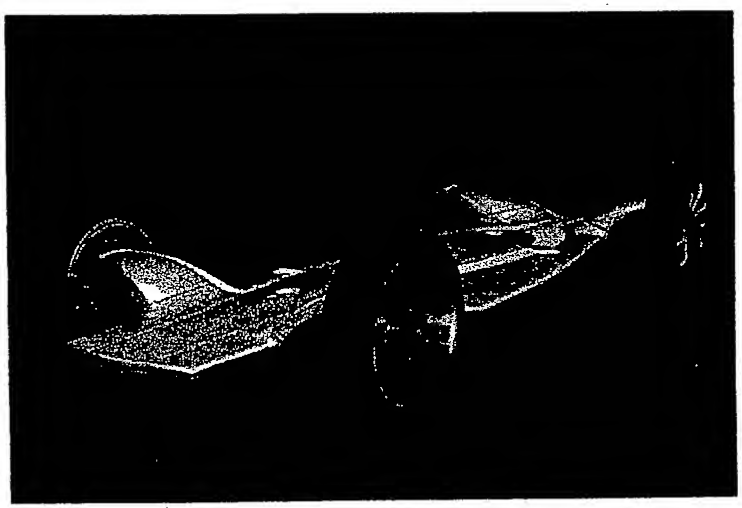

Backup

HEV System Comparison

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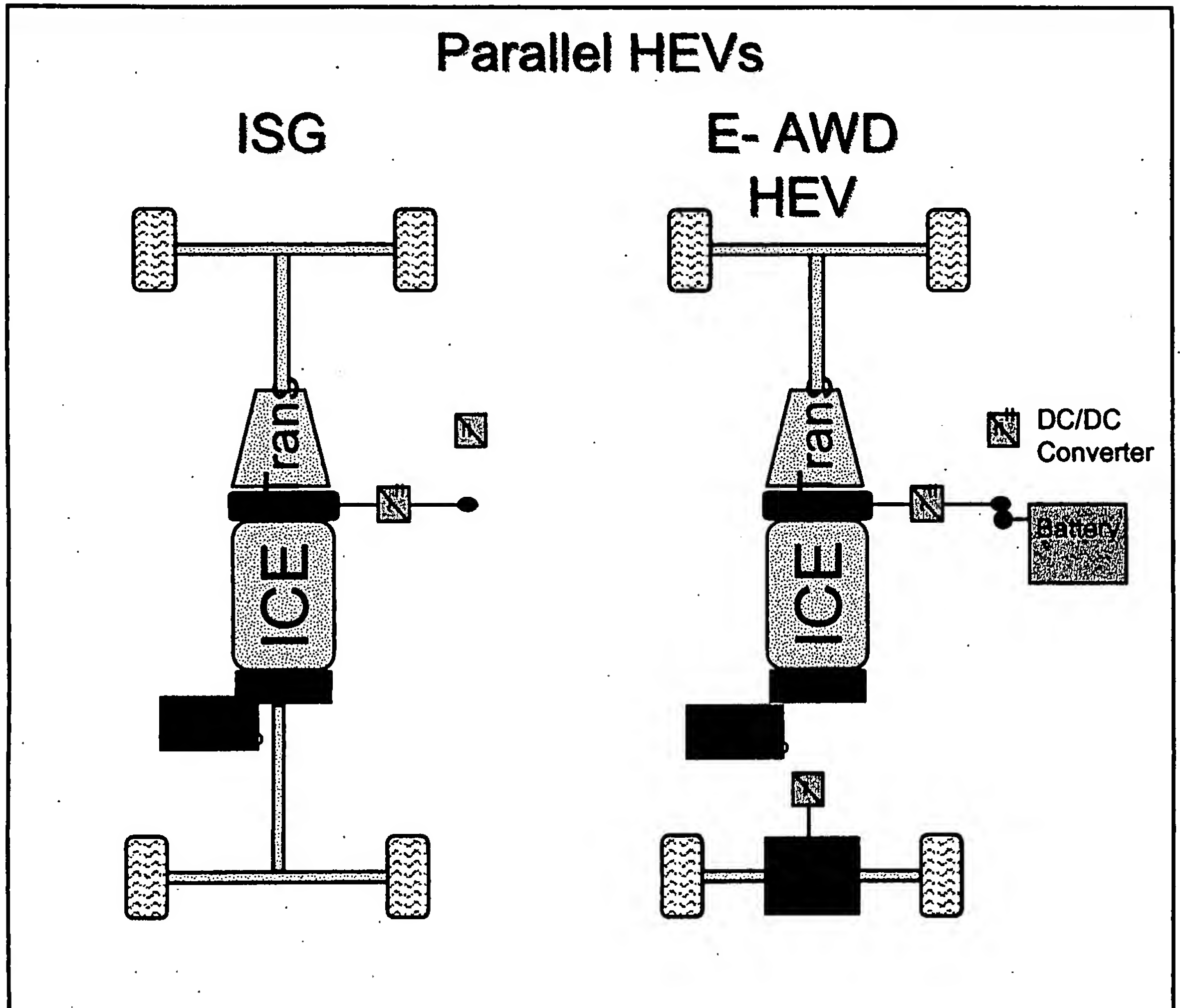

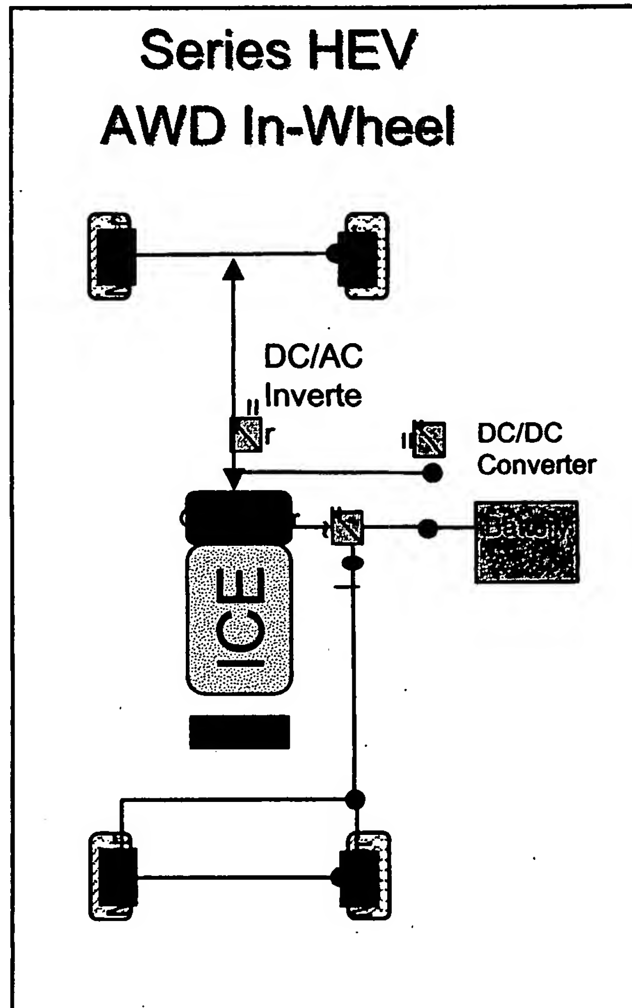

System Efficiencies Gradeability Example

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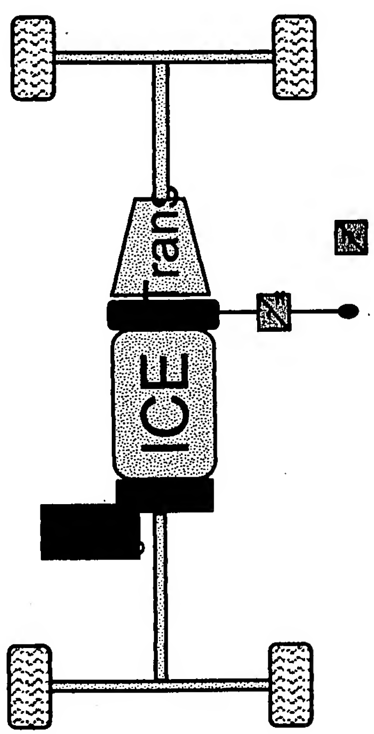
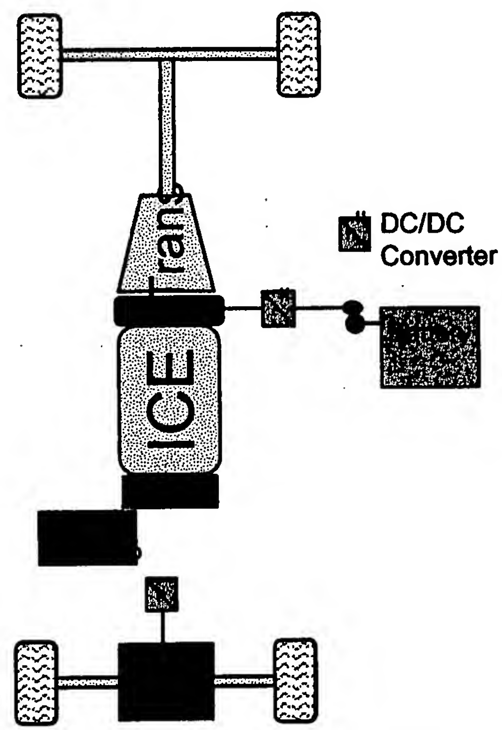
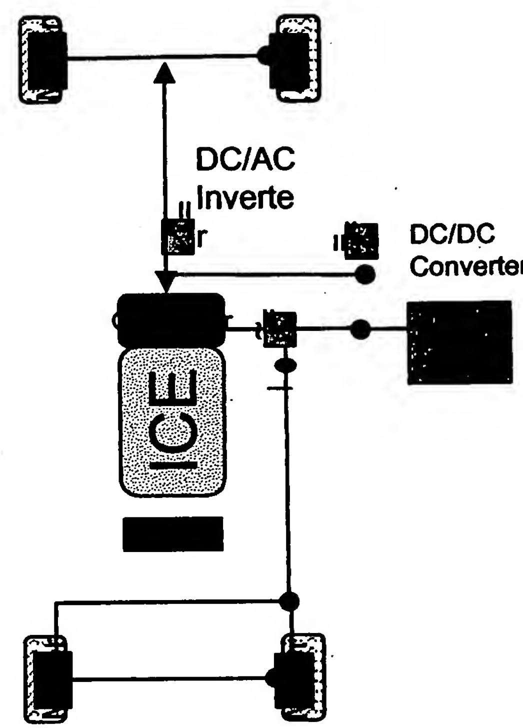
Conventional Driveline	Parallel HEV	AWD Series In-Wheel







Total System : Efficiency	27%	32%	45%

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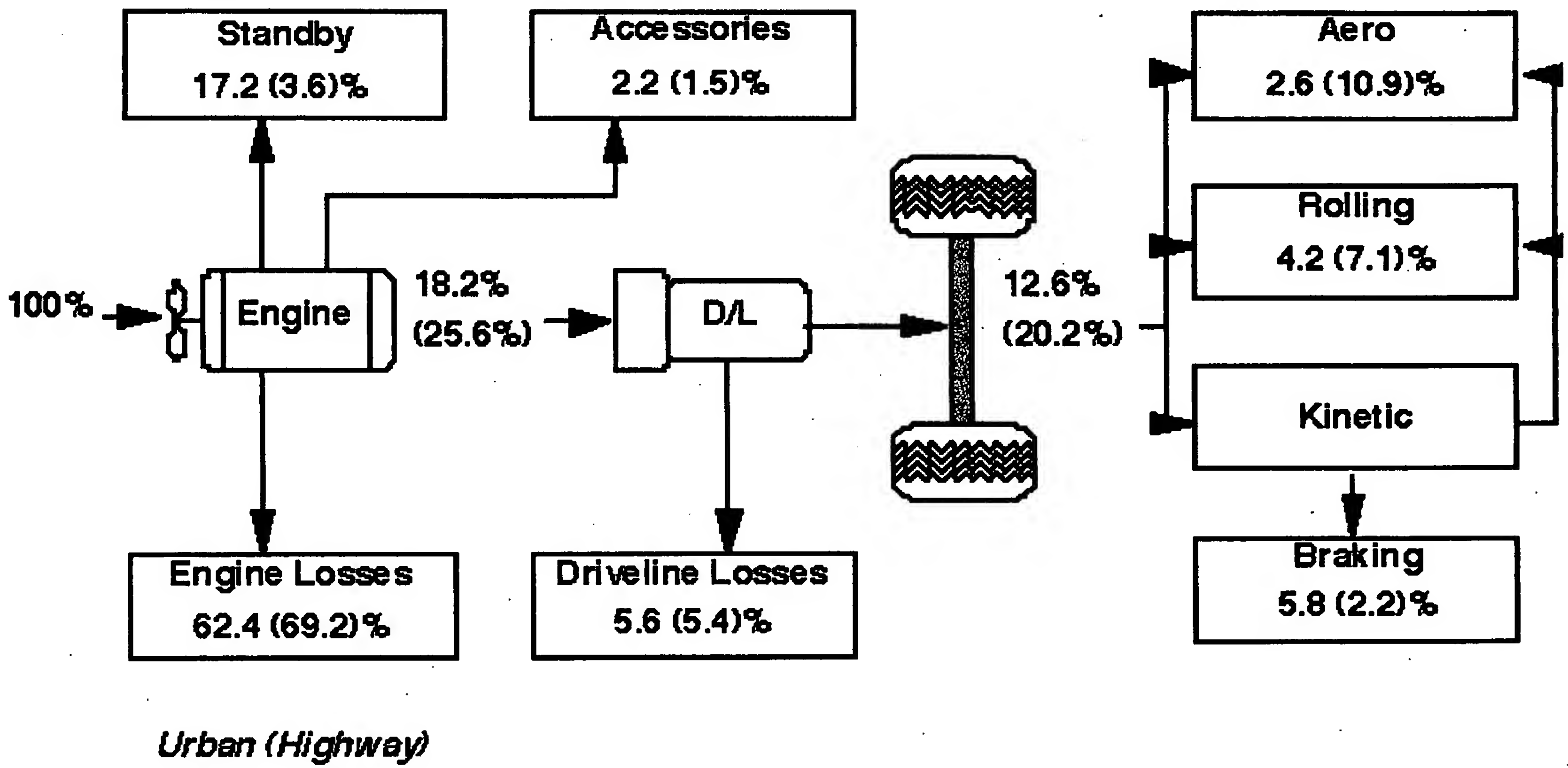

•Figure 5-1. Energy Distribution in a Mid-Size Vehicle

OEM Product Plans – HEV Introduction

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OEM	Pre -2002	2002	2003	2004	2005	2006
TOYOTA	 Prius (THS) Jpn, NA, EU	 Estima (THS-C) Japan  Crown (MHS) Japan	 Lexus RX330	 RAV4, Highlander?		
HONDA	 Insight Japan/NA/EU	 Civic Sedan Jpn, NA		 CR-V?		
GM			 Tahoe/Silverado NA		 Vue, NA	 Epsilon
FORD			 Escape (NA)	 Maverick (EU)		 Volvo XC90 ? NA, EU
DAIMLER CHRYSLER				 Ram NA		Mitsubishi – Sebring, NA ? Smart MCC, EU
NISSAN	 Tino; Japan					Nissan SUV (w/Toyota THS)
VW	 Duo; EU					